



Jet Propulsion Laboratory  
California Institute of Technology

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# Arraying Technologies For Deep Space Communications and Other Applications

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# Today's Agenda

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- Introduction
  - The Deep Space Network
  - History of Arraying Large Antennas: JPL and Elsewhere
  - Alternate Arraying Concept for the DSN
- The Breadboard Array
  - Block Diagram
  - Electronics and Antennas
  - Array Signal Processing
  - Antennas, RMS performance and issues identified for high frequencies
- Interferometric Tools Developed to Characterize Array and Antenna Performance
- Antenna RF Performance
  - Antenna efficiency, noise temperature, thermal effects...the whole 9 yards
- Spacecraft Signal Combining
  - MRO Combining Results
  - Cassini Combining Results
- Other Applications of Arraying
- Summary and Current Plans

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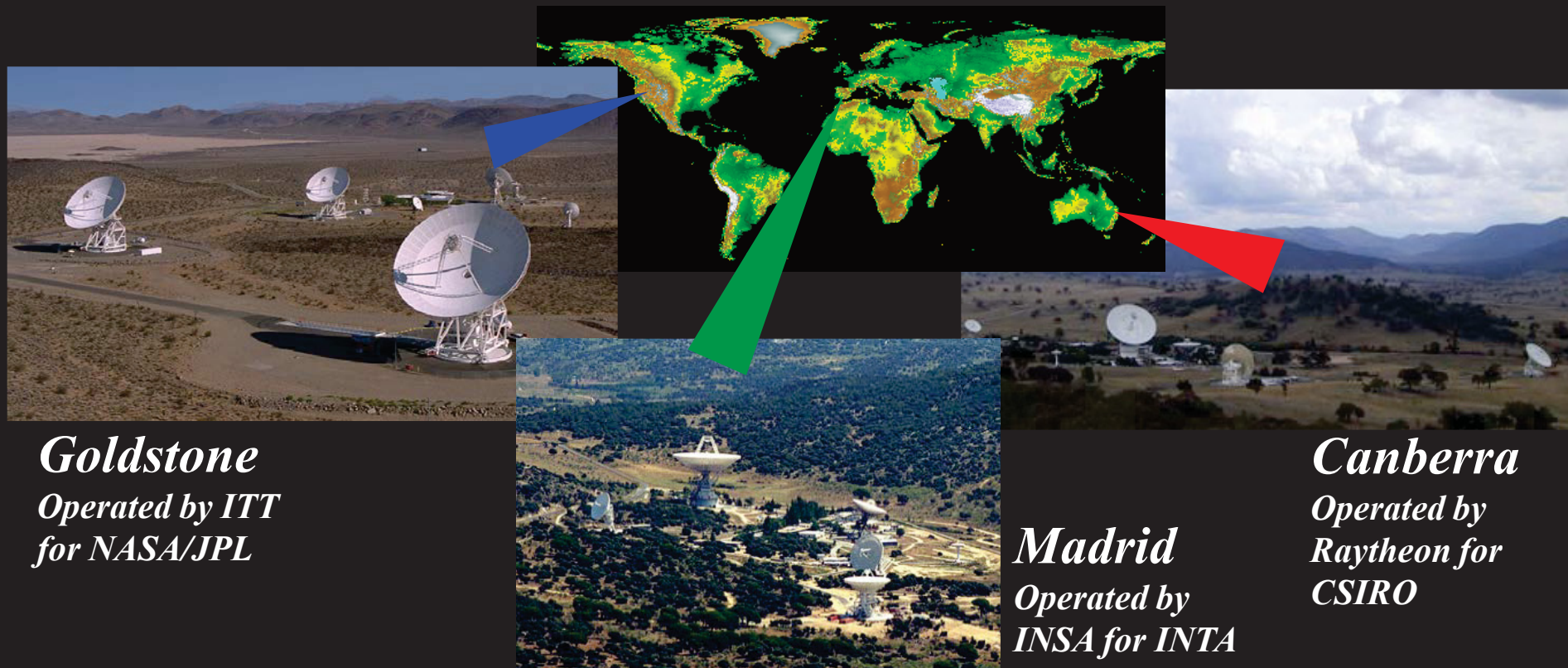




# Today's Deep Space Network

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- Three major tracking sites around the globe provide continuous communications and navigation support for the world's deep space missions



## Arrays: What Has Already Been Accomplished – Elsewhere

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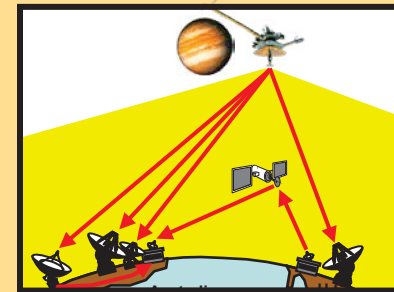
- Arraying has been widely used by the radio-astronomy community
  - The Very Large Array (VLA) arrays 27 25m antennas in New Mexico. It has been operational (24x7) since 1980
  - The Westerbork telescope in Netherlands arrays 14 25m antennas. It has been operational (24x7) since 1970's
  - The Australian Telescope National Facility (ATNF) arrays 6 22m antennas. It has been operational (24x7) since 1990
  - Other ad-hoc arrays have been created as part of the international VLBI community across multiple continents
- Among major new array activities are
  - Extended Very Large Array (EVLA) will have 36 25m antennas in New Mexico
  - ALMA will have 64 12m antennas in Chile
  - The Square km Array (SKA) will have up to 4500 12m antennas at a TBD location
  - The Australian CSIRO is constructing an SKA-precursor (ASCAP)
  - The South Africans are constructing an SKA-precursor (MeerKAT)

## Arrays: What Has Already Been Accomplished – JPL

- DSN arraying was anticipated in the NASA's 1980 Network Consolidation Study (JPL & GSFC)
- The DSN supported Voyager's Uranus ('86) and Neptune ('89) encounters with arrays of antennas (including the VLA)
- The DSN helped save the Galileo mission (when its HGA failed to deploy) through routine use of antenna arrays (including Parkes)
- The decision to expand the DSN with 34m antennas rather than 70m (made in the mid 80s) was predicated on the use of arraying
- Recent research suggests the most economical element size for a new DSN array is between 10m and 15m
- An array breadboard technology development task was completed in 2008
  - Developed antennas and components that can be mass-produced for low cost
  - Demonstrated software algorithms and hardware components using three 6m antennas at JPL and Caltech



DSN arrays enabled Galileo to succeed after its HGA failed to deploy



6-m DSN Array  
breadboard antenna  
dedication



# Alternate Concept to Historical DSN Arraying

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- Between 2002 and 2007 NASA/JPL investigated using an array of a large number of small diameter (LNSD) antennas as the foundation of the next generation Deep Space Network
  - Significantly larger number of antennas and more complex than currently implemented
  - Not reasonable to simply scale the current operations concept
- Recent developments in both antenna costs and electronics costs suggests that an array of antennas (e.g., 12-m diameter) of sufficient number to equal the effective area of a 34-m (or even a 70-m) diameter antenna can be implemented for less cost.
  - Size and cost of electronics have both been decreasing over time
  - Antenna construction techniques have resulted in much lower cost smaller antennas
  - Operations Costs must be included and also have been studied; however, only when an array of sufficient size is constructed would these costs be properly addressed.
- A new Concept of Operations was proposed by which this new system can be operated and maintained more cost effectively.
  - Completely different paradigm
  - Validation of the new concepts by benchmarking industry was carried out

## Alternate Concept to Historical DSN Arraying (cont'd)

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- Benchmarking results suggest:
  - Rely more than before on industry for implementation and test. What was once a purely government domain is now commonly available in industry.
  - Shift to operations that are centralized and highly automated. The telecommunications industry has already completed such a shift.
  - Employ an automated service request paradigm to support science mission users.
  - Provide an infrastructure that stays technically current by continuous low-level updates to both hardware and software.
  
- These ideas challenge the current operations and maintenance paradigms and suggested areas where efficiencies could be found for *any* ground system including the current DSN



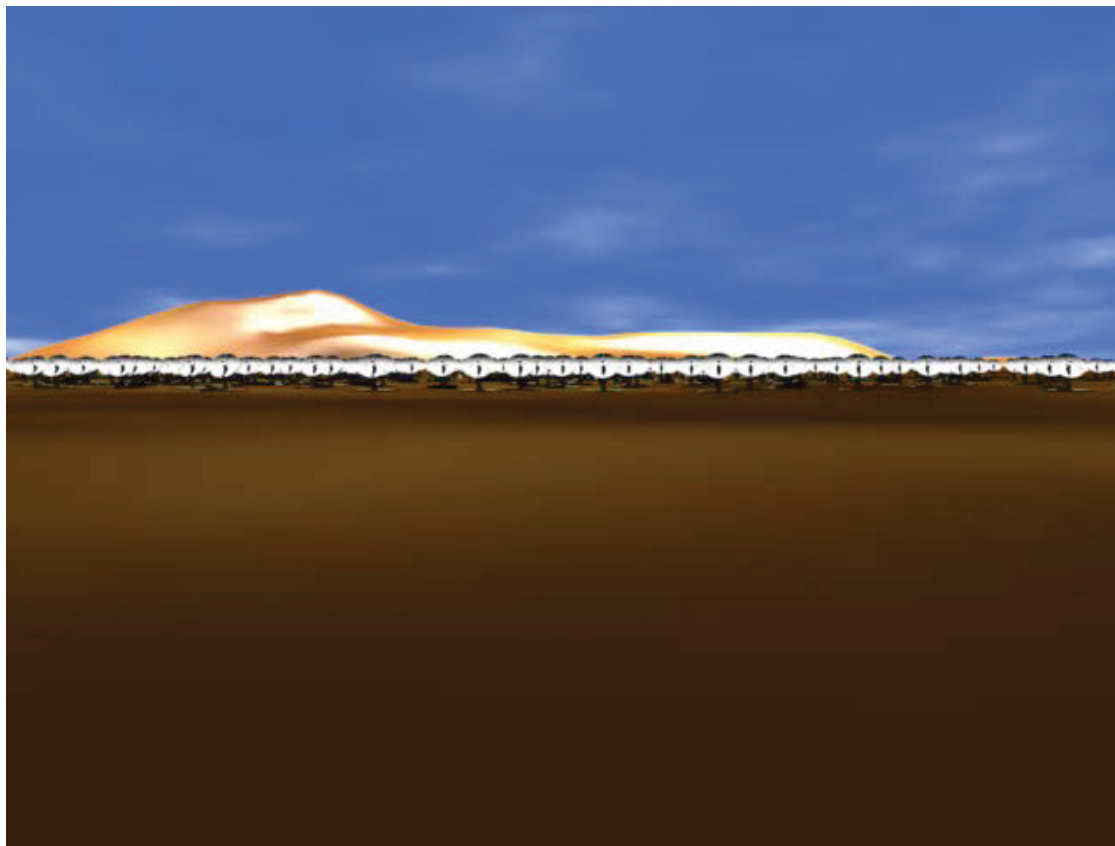
## Alternate Concept to Historical DSN Arraying (cont'd)

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- The array concept proposed for the DSN in 2001 was based on the use of many small, inexpensive antennas; each outfitted with inexpensive electronics; connected through a signal processing system designed to handle up to 1600 inputs; controlled by a modern centralized monitor and control system.

Artist's Rendition  
of one possible  
DSN Phased Array  
Antenna

IN MOTION





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## ➤ The Breadboard Array

- Block Diagram
- Electronics and Antennas
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## ➤ Interferometric Tools Developed to Characterize Array and Antenna Performance

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- Antenna efficiency, noise temperature, thermal effects...the whole 9 yards

## ➤ Spacecraft Signal Combining

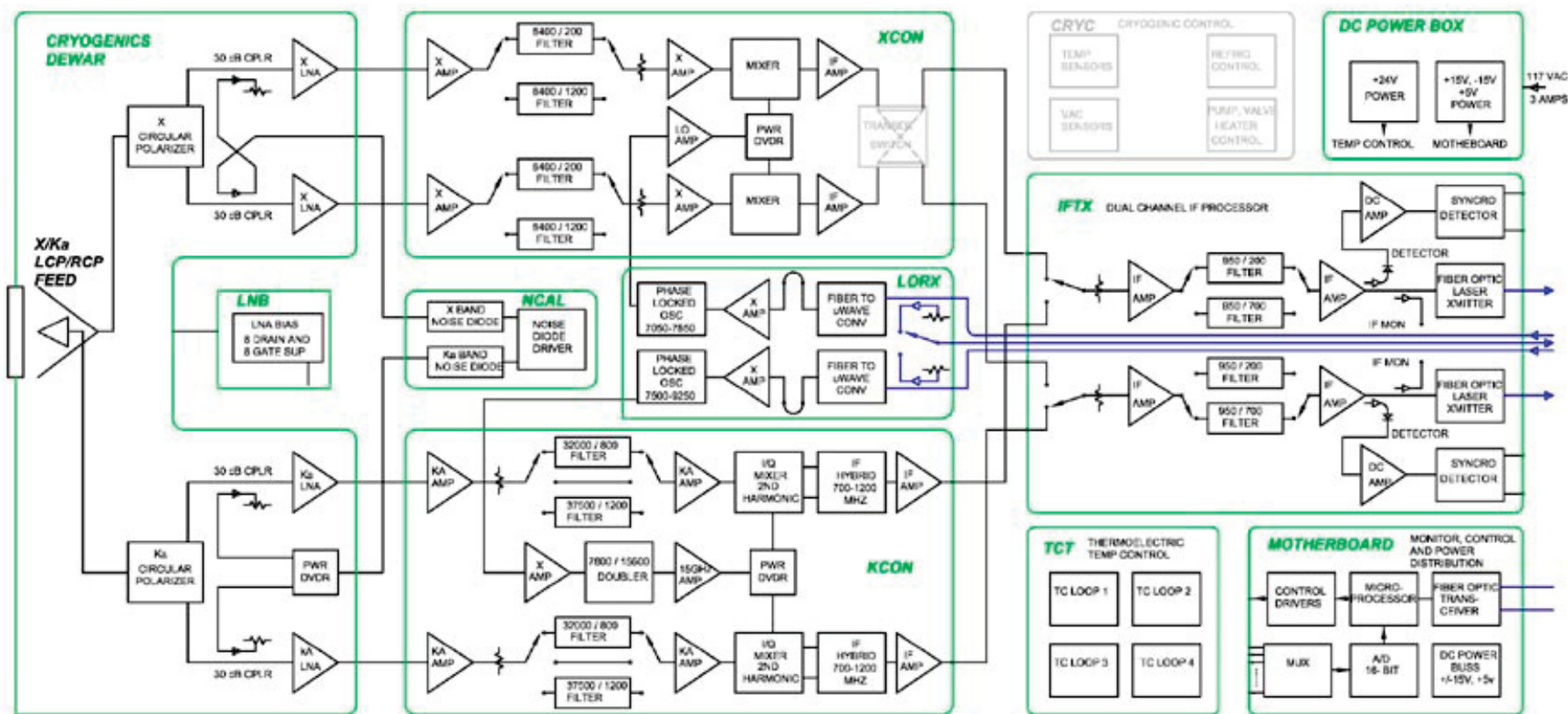
- MRO Combining Results
- Cassini Combining Results

## ➤ Other Applications of Arraying

## ➤ Summary and Current Plans

# DSN Array Receive Electronics: Block Diagram for an Array Element

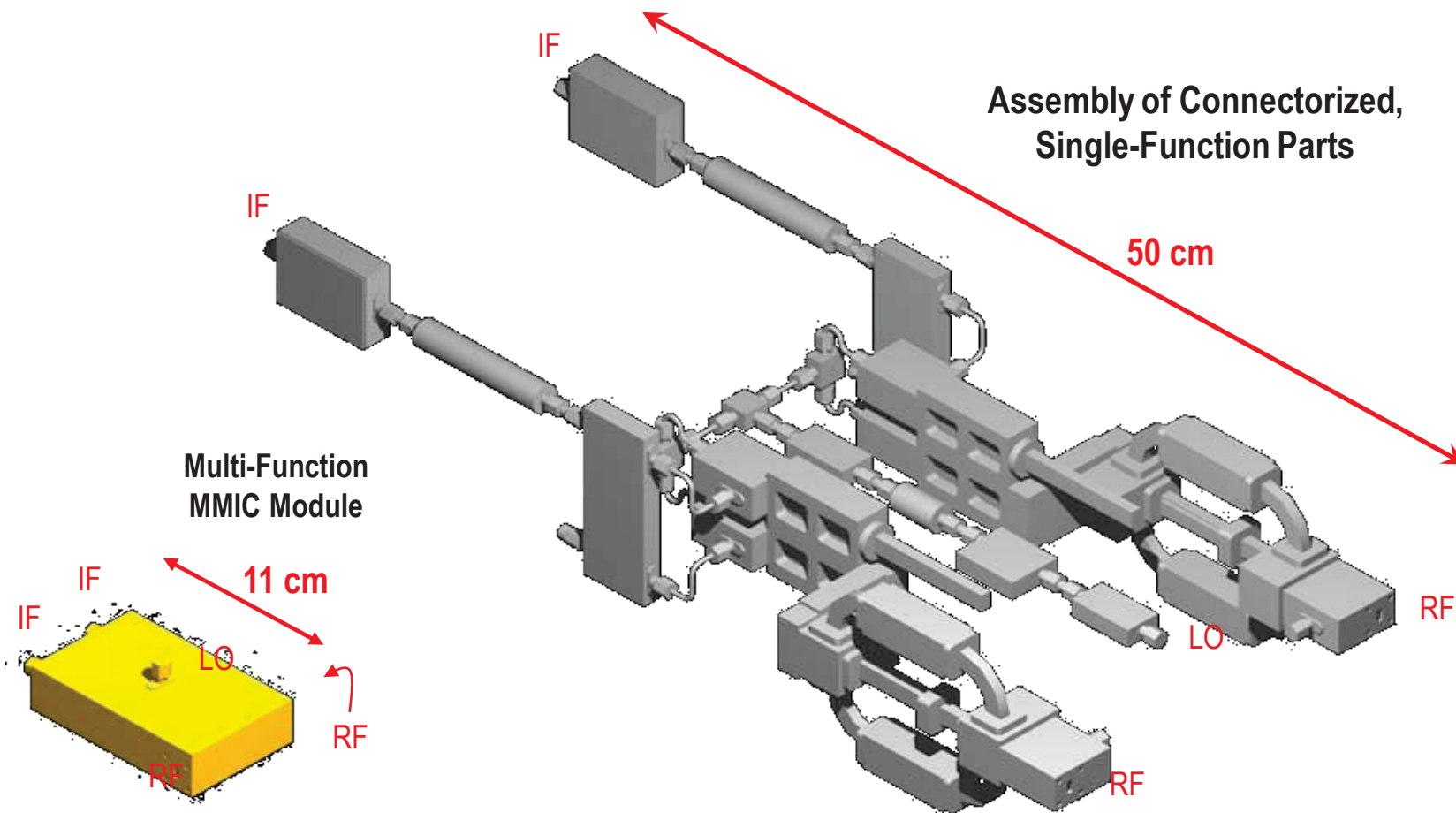
- Block diagram: system is capable of providing simultaneous X/Ka-band downlink



# DSN Array Receive Electronics: Reduced Form Factor

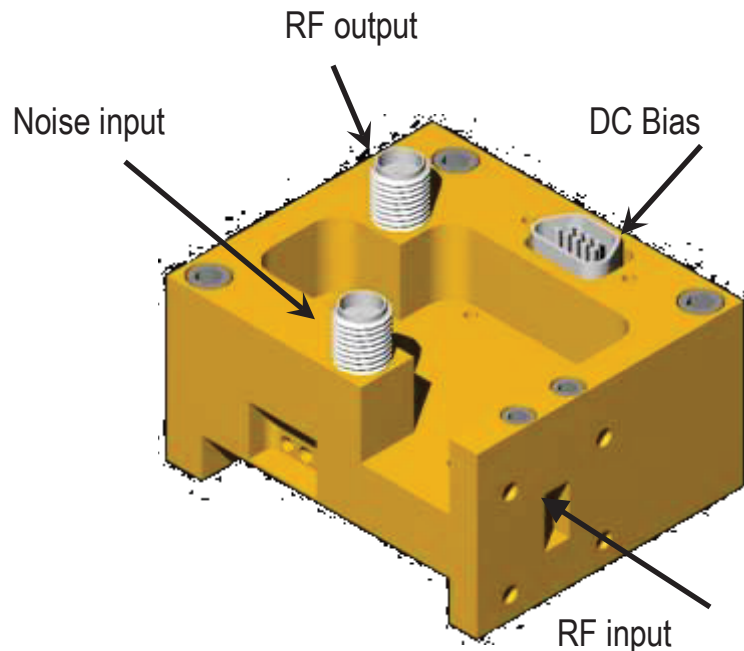
- MMIC Technology to Decrease Array Receiver Cost

Multifunction MMIC packaging of Ka band dual-downconverter for the DSN array reduces size and replication cost by an order of magnitude





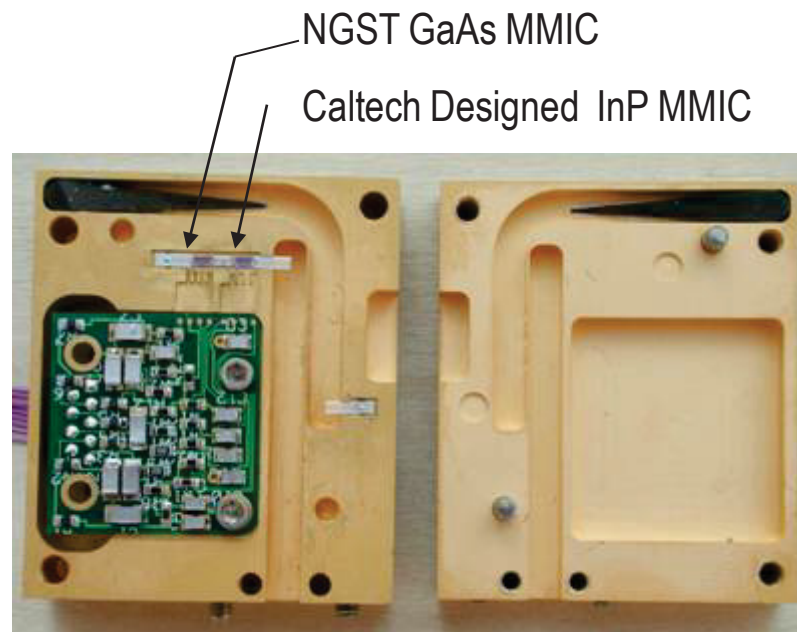
# DSN Array Receive Electronics: Ka Band Low Noise Amplifiers



Dimensions 1.75 x 1.5 x 0.9"

## Performance

- Noise temperature 11K
- Gain > 40 dB

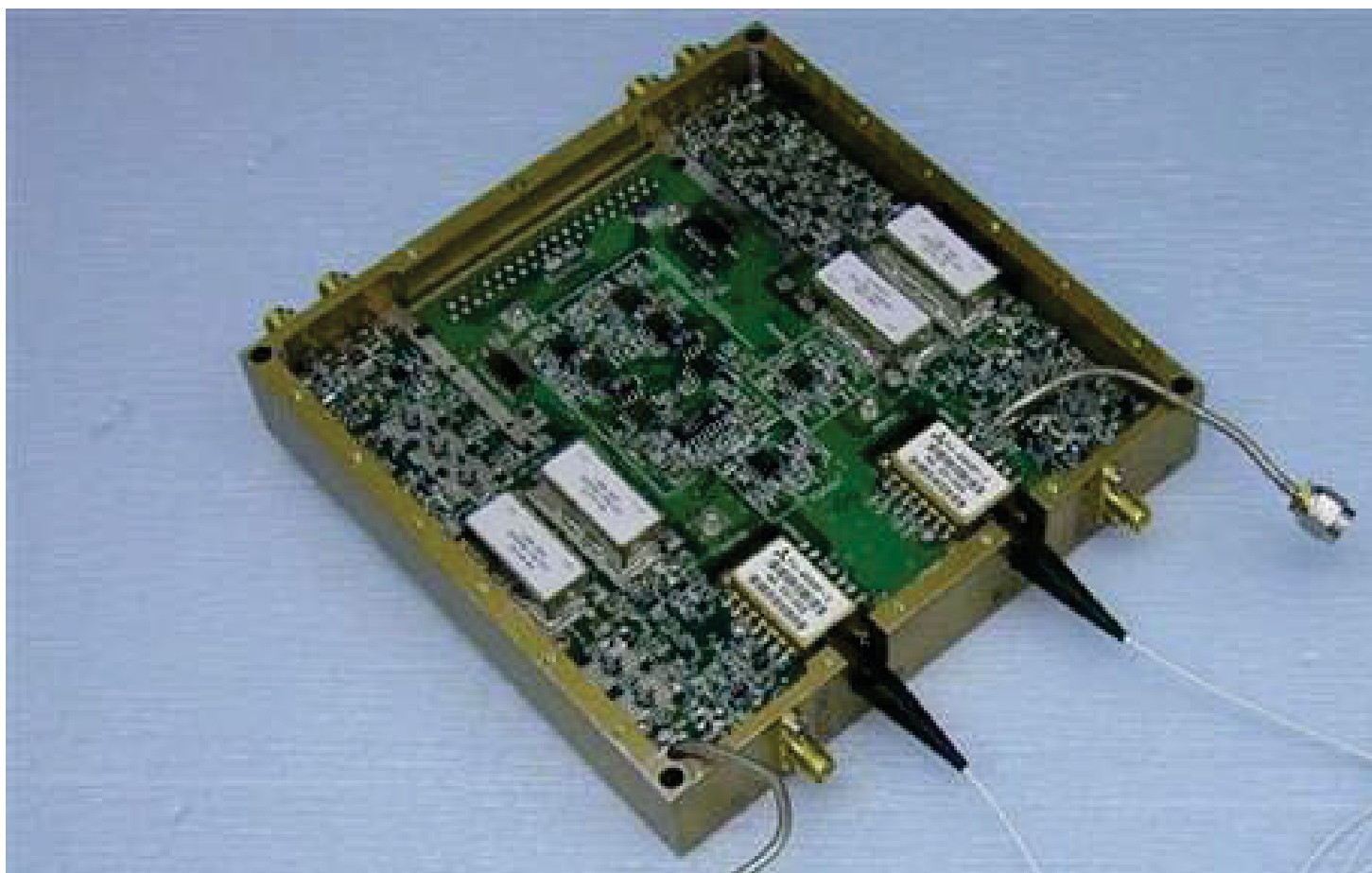


Interior View of Split Block – LNA includes Directional Coupler for Noise Calibration Injection

# DSN Array Receive Electronics: RF/IF Module

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IF processing module provides LNA selection, gain control, filtering, power monitoring, and conversion to fiber for transmission to control room which may be a few km away. Size is approximately 5" square.



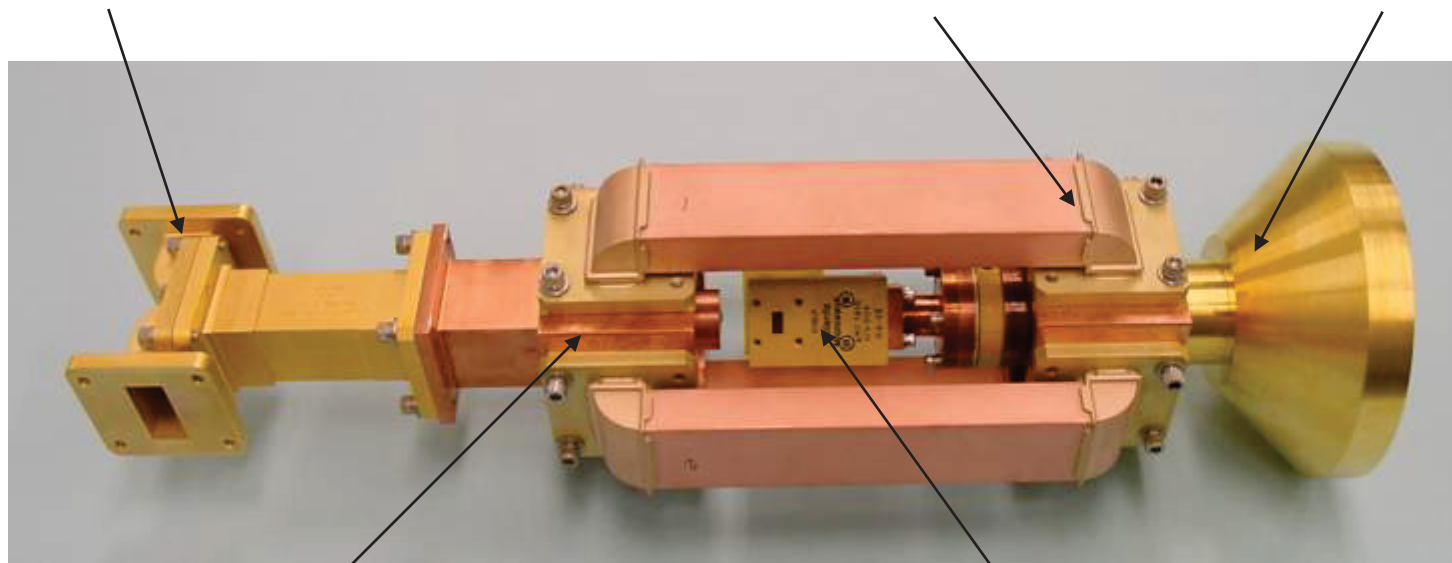
# DSN Array Receive Electronics: X/Ka-band Dual Circular Polarized Feed

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X-Band Polarizer

Coaxial Turnstile Junction

Corrugated Horn



Square Turnstile Junction

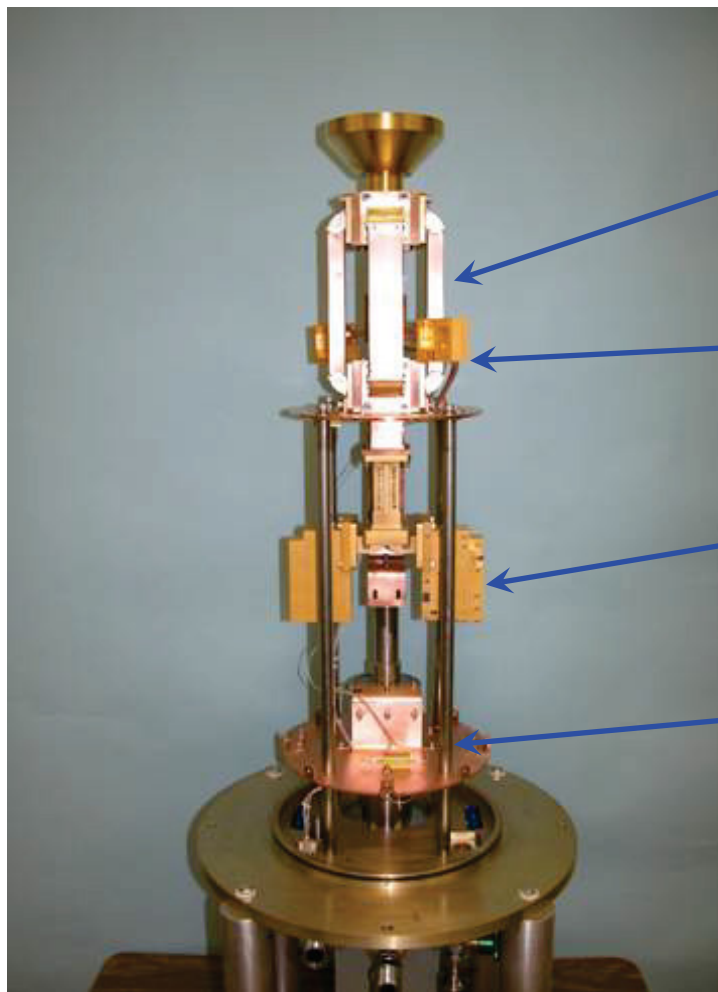
K<sub>a</sub>-Band Polarizer

- Feed covers 8.0 to 8.8 GHz and 31 to 38 GHz
- Entire feed is cryogenically cooled for very low noise performance

# DSN Array Receive Electronics: Cryo assembly (w/o dewar)

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- Concept to develop low cost electronics... “front-end in a box”



Dual frequency feed – dielectric rod in corrugated horn

31-38 GHz, Ka LNA' s

8.0-8.8 GHz, X LNA' s

CTI 15K cryocooler



# DSN Array Receive Electronics: Feed Tower and Electronics

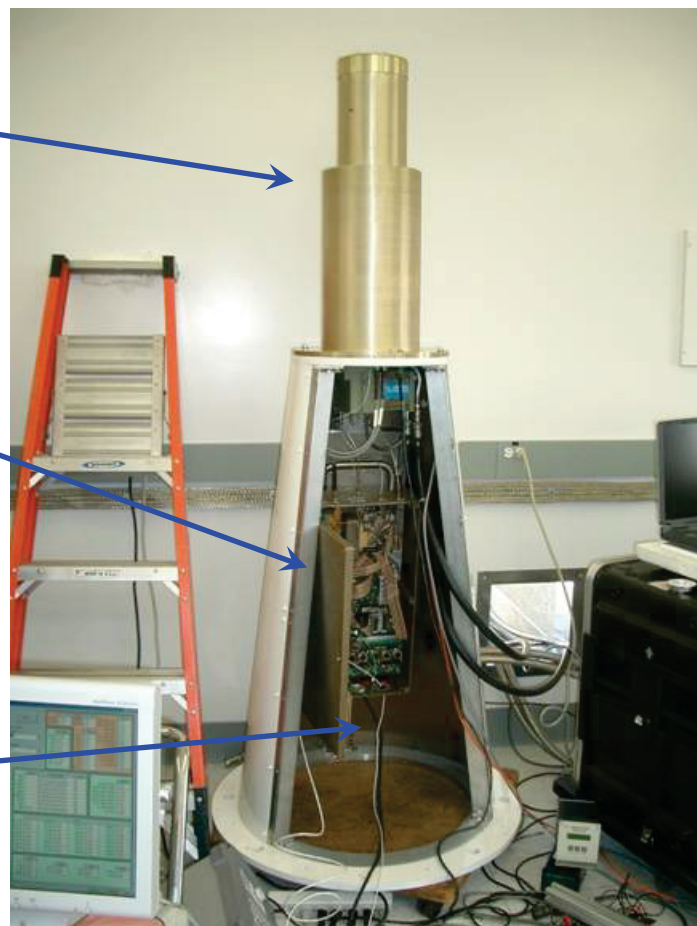
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- Concept to develop low cost electronics... “front-end in a box”

Vacuum dewar containing dual-frequency, dual circular polarization feed and 4 LNA's all cooled to 15K

Receiver box containing downconversion, LO, and IF modules mounted on a temperature controlled plate

Connections to control room are AC power and 6 optical fibers for LO, IF, monitor, and control.



# The Breadboard Array – Signal Processing

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- Array Processor consists of custom designed analog and digital electronics
  - FPGAs
  - Embedded PowerPC processors
  - Linux workstation
- Provides both correlation and combining of entire 500 MHz signal from antennas
  - Full Spectrum combining that is independent of signal format, coding, data rate, modulation, etc.
  - Correlation to develop interferometric baseline fringe amplitudes and phases
  - Combining to coherently sum the IF from multiple inputs to form a single beam
- Interferometer Mode
  - Cross-correlation data used to characterize performance of antennas
- Combining mode
  - Cross-correlation data used in feedback loop to adjust phase and delay in real time
- Fiber optic lines transport the analog IF signal from the antennas to the array processor
  - Lines vary in length up to 1 kilometer
  - 50 dB dynamic range
  - Group delay less than 100 picoseconds
- Sampler
  - 1280 MHz; lowest rate that allows for design of anti-aliasing filter with 1 dB cutoff at band ends, image rejection > 30 dB, group delay variation < 0.2 dB

# Proposed Large Array of Small Antennas

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70-m Antenna

Truck and Van



One concept is to have a large number (40-400) of 12-m antennas at *each* site

# The Breadboard Array - Overview

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- A 3-element array was constructed to investigate the many aspects of arraying a large number of small antennas
- 2 ea x 6 meter Gregorian antennas
  - 1 ea x 12 meter Cassagrainian
  - Simultaneous operation at 8 and 32 GHz, dual polarization
  - Cryogenic LNAs
  - Downconversion of RF to IF 950 MHz (500 MHz bandwidth)
  - Digital combiner feeds standard DSN telemetry receiver
  - Described in previous IEEE Aerospace conference(s)



12 meter antenna



6 meter antenna



# The Breadboard Array: Typical Performance Specifications

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12-m Antenna



2 x 6-m Antennas

Requirement	X-band Value	Ka-band Value
Element Size (diameter, m)	12	12
Reflector Surface Accuracy (total, mm)	0.305	0.305
Array Size (N)	400	400
A/T (m <sup>2</sup> /K)	1440	620
Sky Coverage		
Elevation	6° - 90°	6° - 90°
Azimuth	± 270°	± 270°
Tracking rate, max (°/min)	24	24
Slew rate, max (°/min)		
Elevation	45	45
Azimuth	180	180
RF Frequency Band (GHz)	8.0 - 8.8	31 - 38
IF Bandwidth (MHz)	500	500
Correlator Processing Bandwidth (MHz)	100	100
Combiner Processing Bandwidth	100 (16*)	100 (16*)
Polarization	Dual CP	Dual CP
Array Beams/cluster	16	16
Gain Variation (dB)	< 0.2	< 0.2
Phase Noise (dBc/Hz)		
1 Hz offset	-65.7	-65.7
10 Hz offset	-73.3	-73.3
100 Hz offset	-75.2	-75.2
1000 Hz offset	-75.2	-75.2
10000 Hz offset	-75.2	-75.2
Allan Deviation		
1 s integration	3.9 x 10 <sup>-13</sup>	3.0 x 10 <sup>-13</sup>
10 s integration	4.6 x 10 <sup>-14</sup>	3.0 x 10 <sup>-14</sup>
1000 s integration	4.5 x 10 <sup>-15</sup>	1.4 x 10 <sup>-15</sup>
3600 s integration	4.5 x 10 <sup>-15</sup>	1.4 x 10 <sup>-15</sup>

\* Bandwidth implemented on breadboard

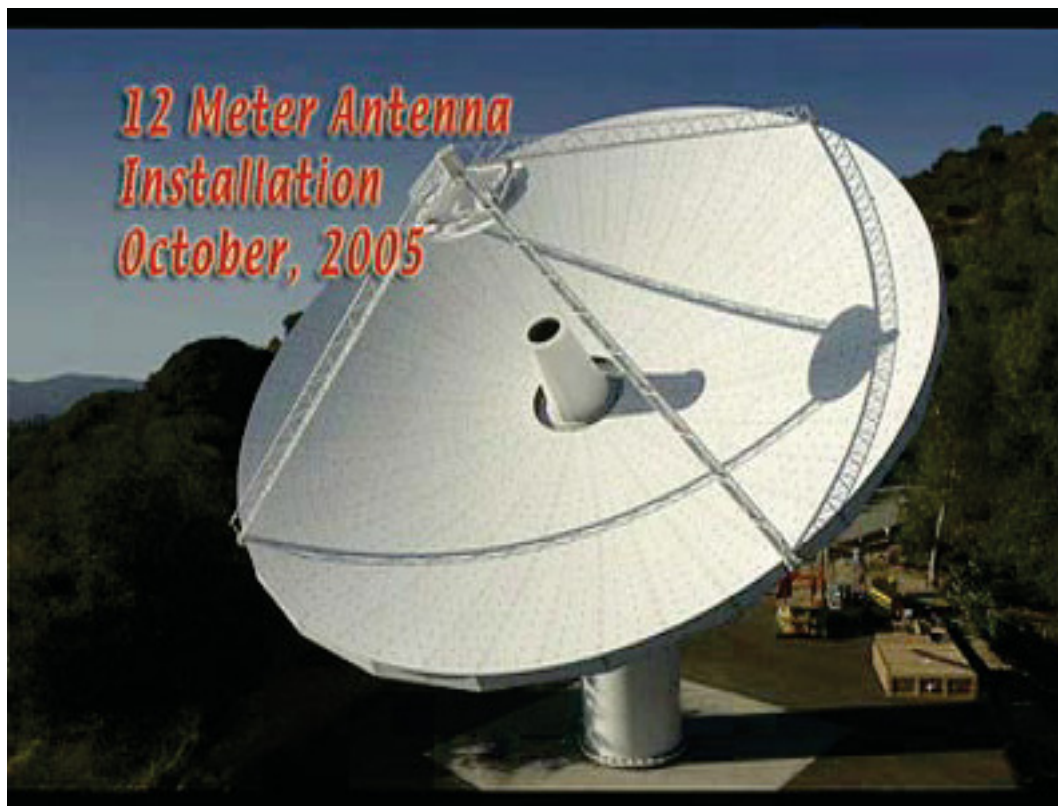


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# The Breadboard Array – 5 Days to Assemble 12m Antenna

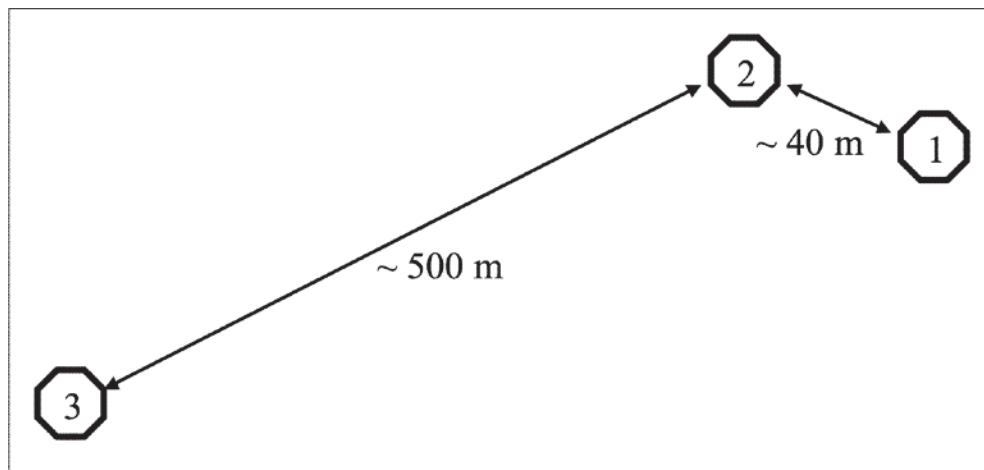
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# The Breadboard Array - Configuration

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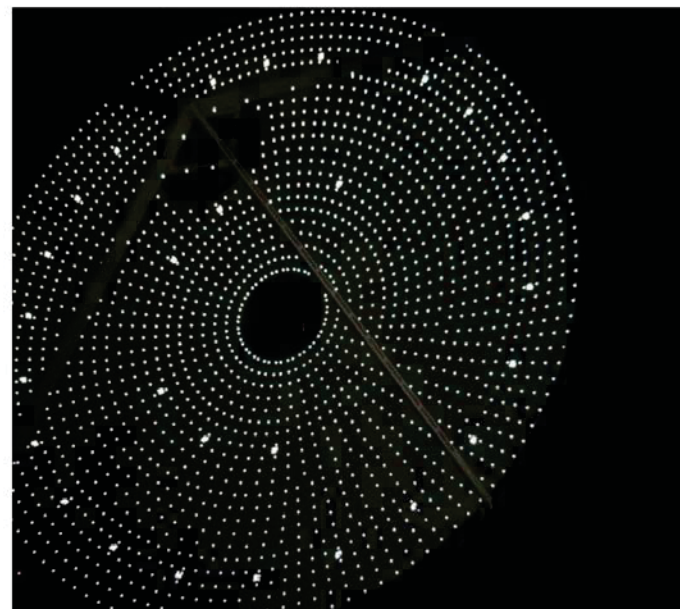
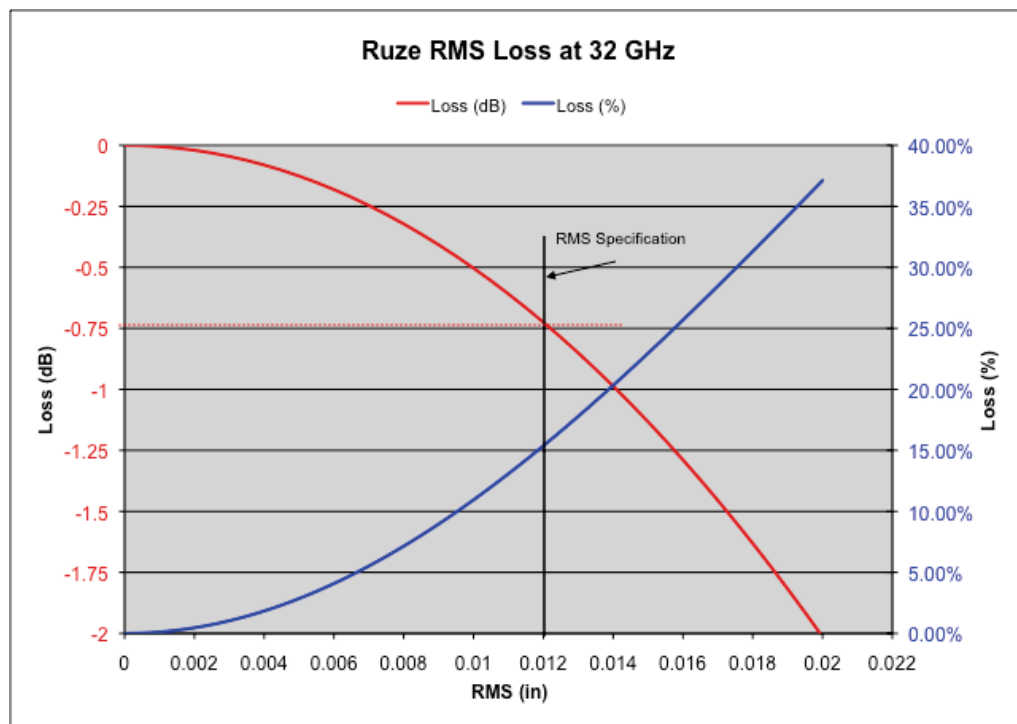




# The Breadboard Array - Antennas

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- Focus on the 12-m antenna since it is more representative of an element planned for the DSN Array.
- Figure-of-merit for an antenna is the total “smoothness” of the surface. The measure is the root-mean-square of the difference between what we want and what we get. Referred to as the “RMS”.



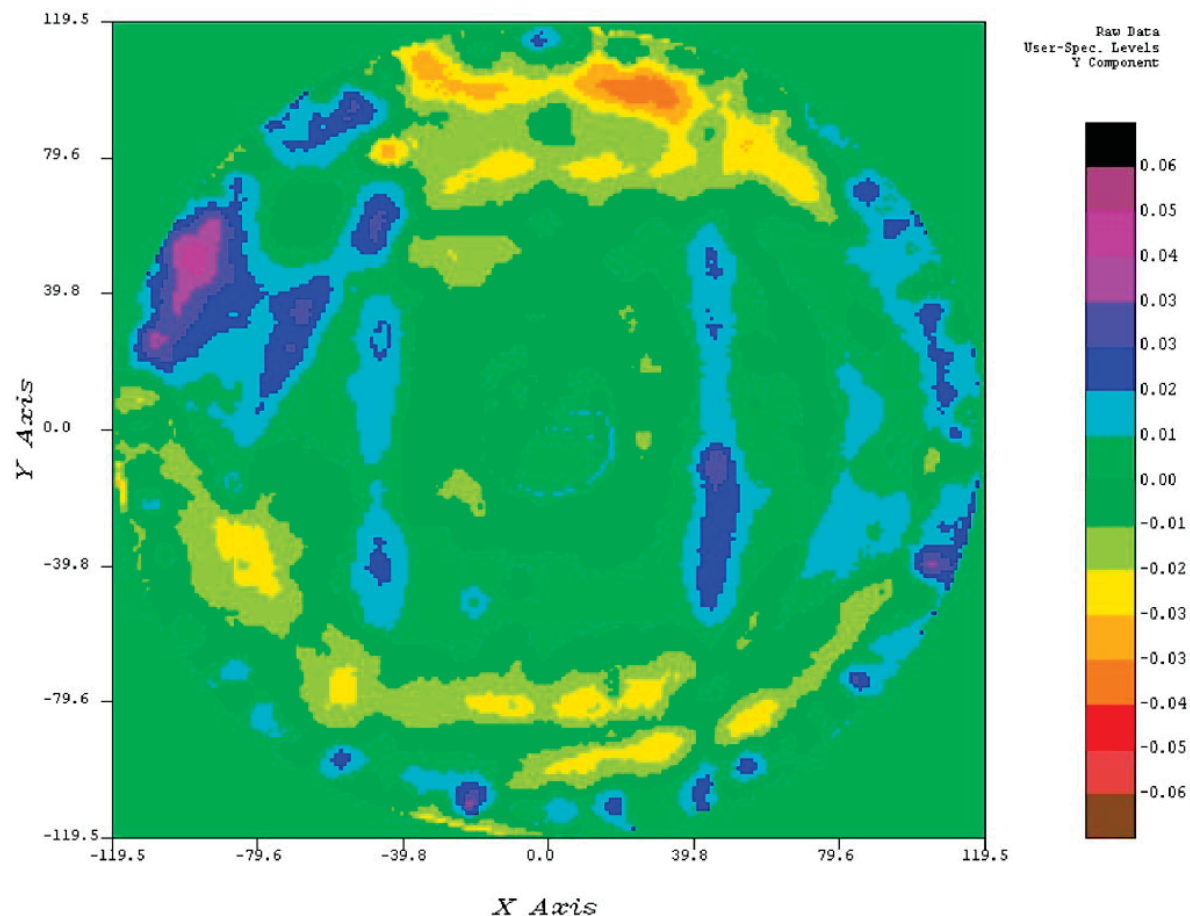
**Figure 7.** Photogrammetry Target Illumination at Night



# The Breadboard Array - Antennas

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- 6-m Antenna RMS Performance.  $\text{RMS} = 0.009''$ . Further tests show efficiency = 60% for all elevation angles, and Zenith System Noise Temperature = 22 Kelvin, all across a wide range of temperatures. Yay!



# The Breadboard Array - Antennas

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- 12-m antenna – First look. The RMS is meets specification (0.012")

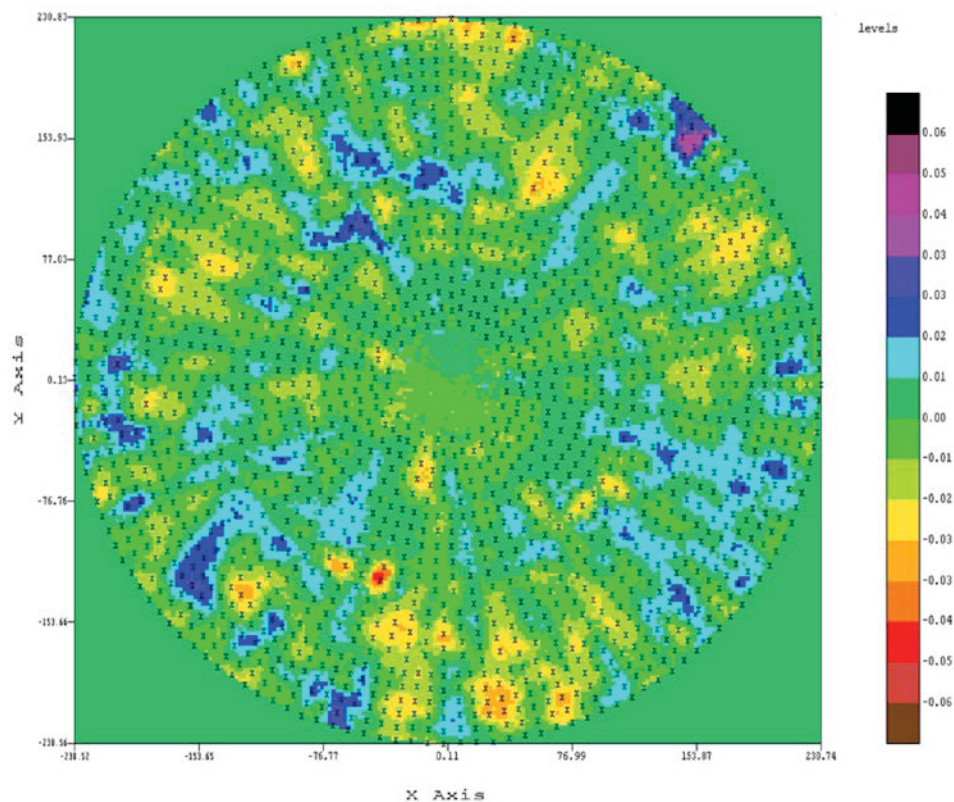
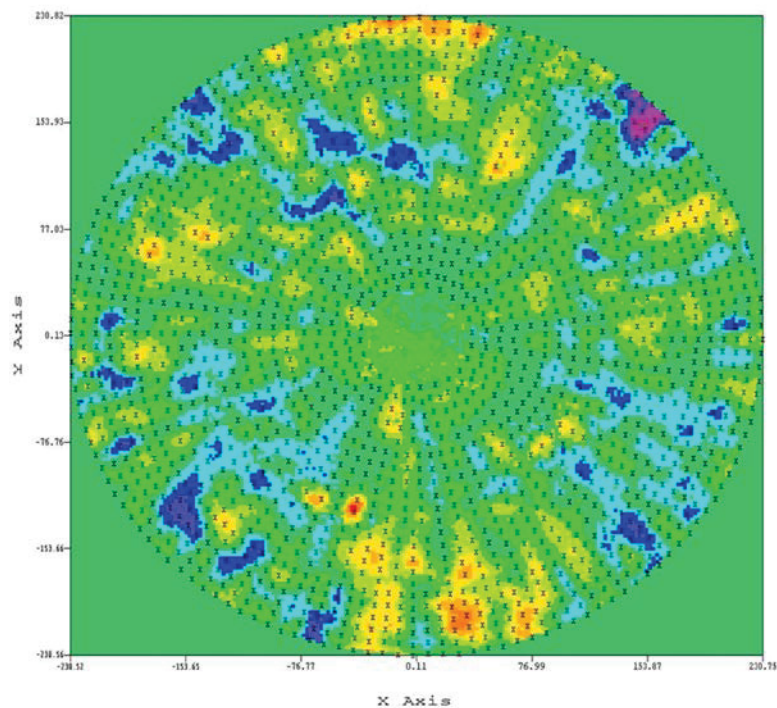


Figure 8. Best Fit Reflector Surface error 0.009" rms at 33.5° (rigging angle)

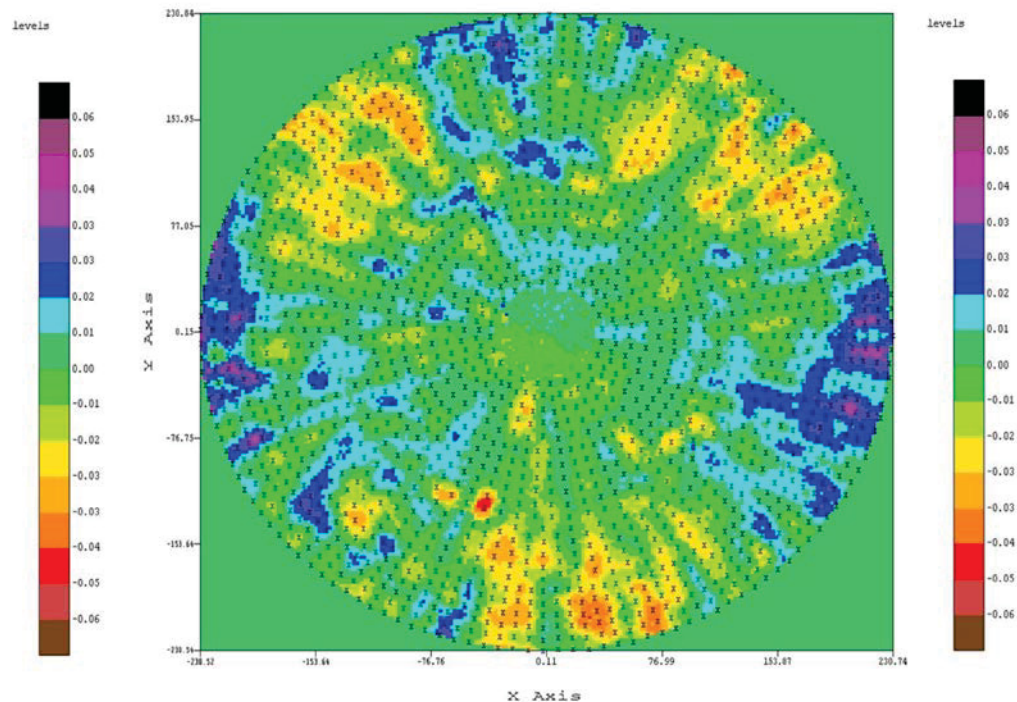
# The Breadboard Array - Antennas

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- 12-m RMS at extreme elevation angles. Still within specification.



**Figure 9.** Best Fit Reflector Surface error 0.0095'' rms at 8° elevation



**Figure 10.** Best Fit Reflector Surface error 0.0113'' rms at 88° elevation



# The Breadboard Array - Antennas

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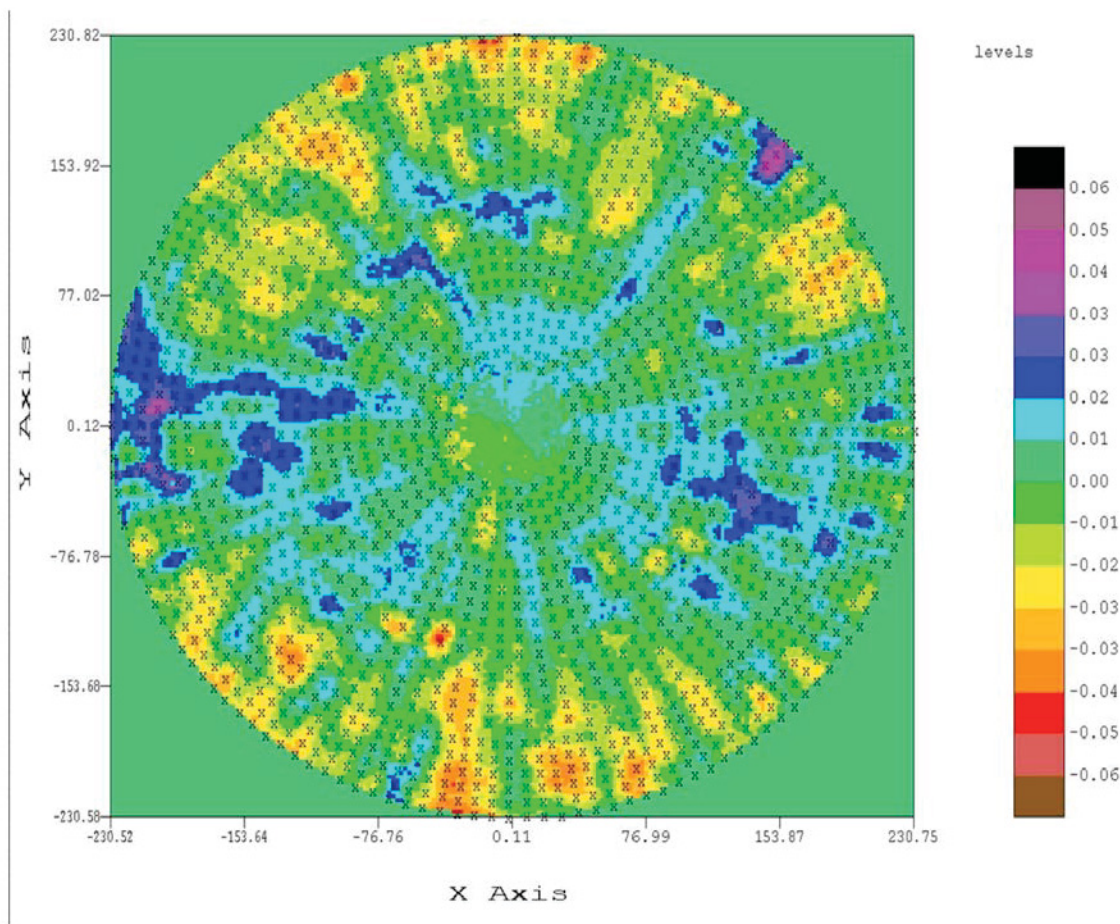
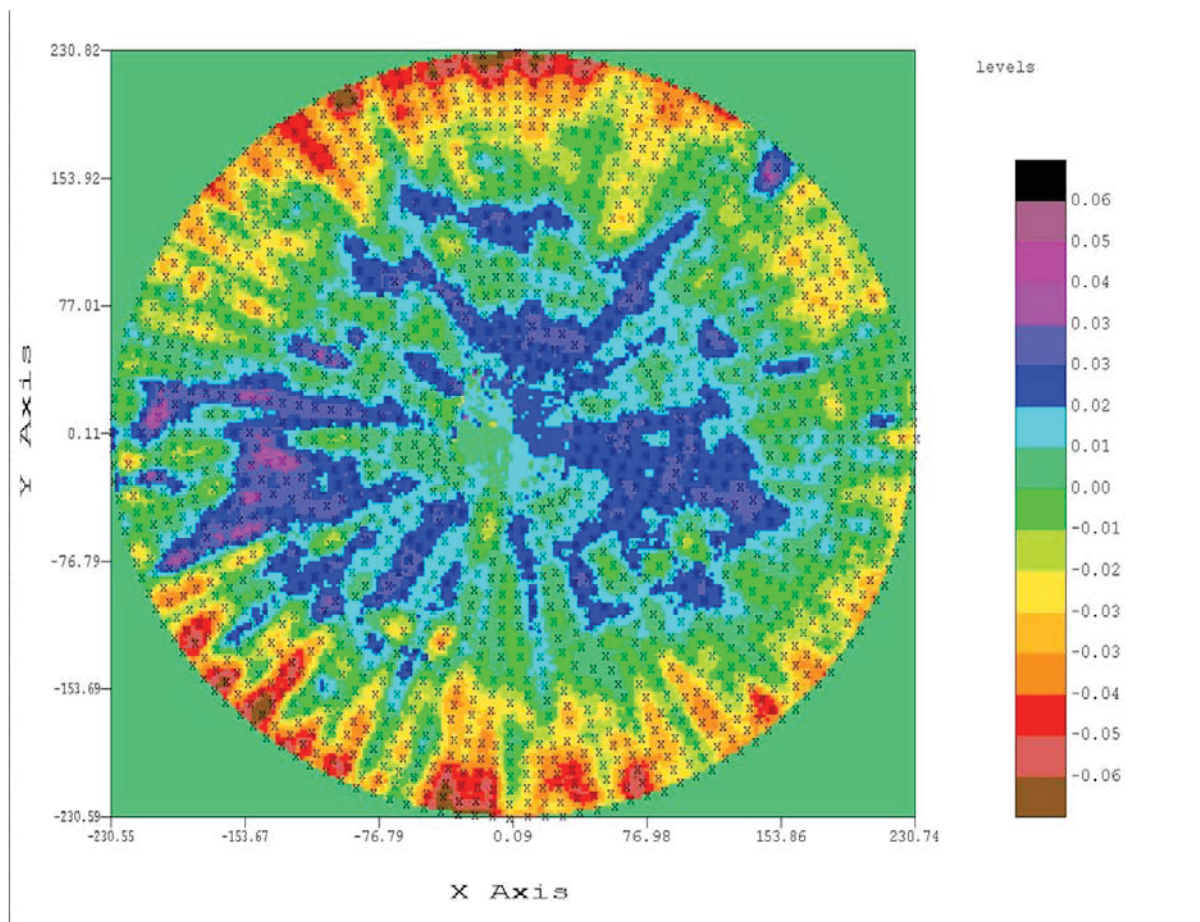


Figure 11. Best fit (Fixed Focal Length) surface RMS error 0.0111" rms at 6 am



# The Breadboard Array - Antennas

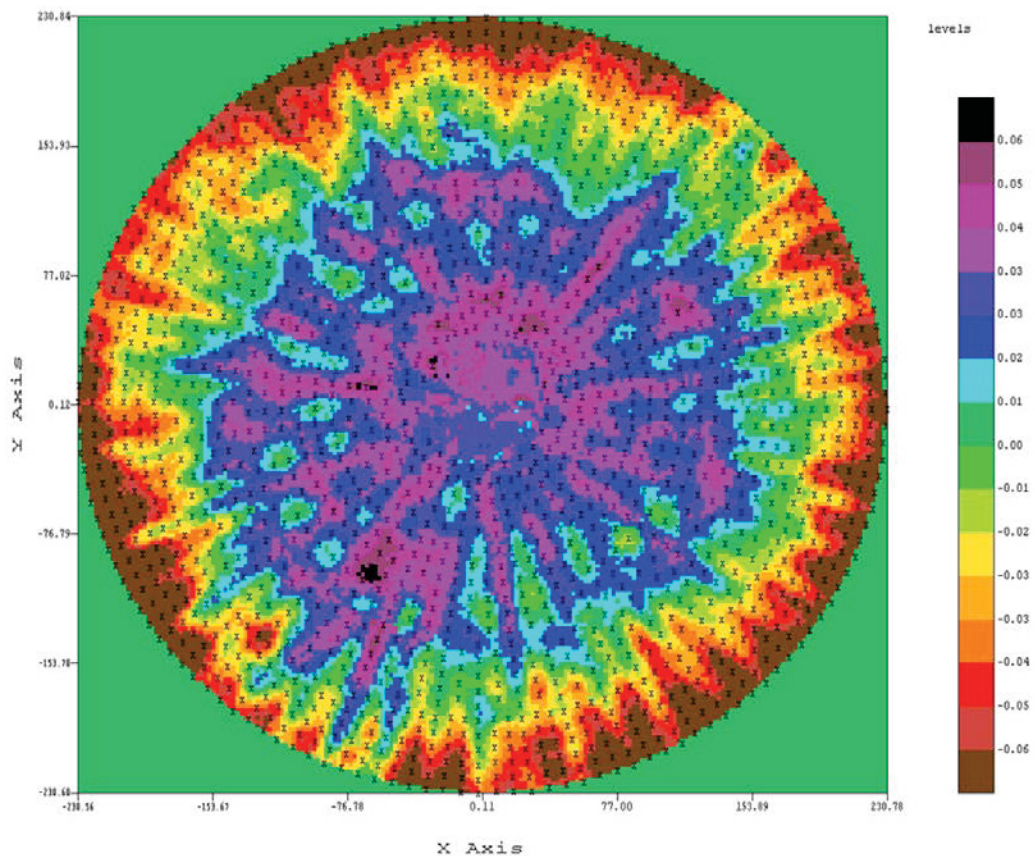
29



**Figure 12.** Best fit (Fixed Focal Length) surface RMS error 0.0172" rms at 8 am

# The Breadboard Array - Antennas

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**Figure 13.** Best fit (Fixed Focal Length) surface RMS error 0.0307" rms at 12 pm

The first indication that the dish can be set to meet requirements...but that there were serious thermal issues to be quantified

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# Interferometric Tools for Antenna and Array Characterization

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- The signal processing system is the heart of the array system
  - Provides the summed up array signal...way cool...
  - Provides an interferometer system that, if used correctly, can be used to characterize *with high signal to noise ratio* the performance of various elements of the system.
- A cross correlation interferometer fringe measures the product of signal from two antennas.
  - Using correlator outputs from 3 baselines (from 3 antennas) can be used to estimate the amplitude and phase for an individual antenna.
  - Correlator amplitude estimates are much less sensitive to receiver gain changes and system temperature variation due to atmospheric effects
  - Used to make very sensitive antenna pattern and subreflector scan measurements (to be shown soon)
- The monitor and control system was capable of supporting very robust scripting via Python
  - Scripts developed for unattended data collection
- Let's just stipulate right off the bat that performance at X-band was nearly as expected in efficiency, noise temperature, pointing, etc. ALL THE EXCITEMENT HAS BEEN AT KA-BAND! **Therefore, the focus of the antenna characterization of this talk will be for 32 GHz.**





# Today's Agenda

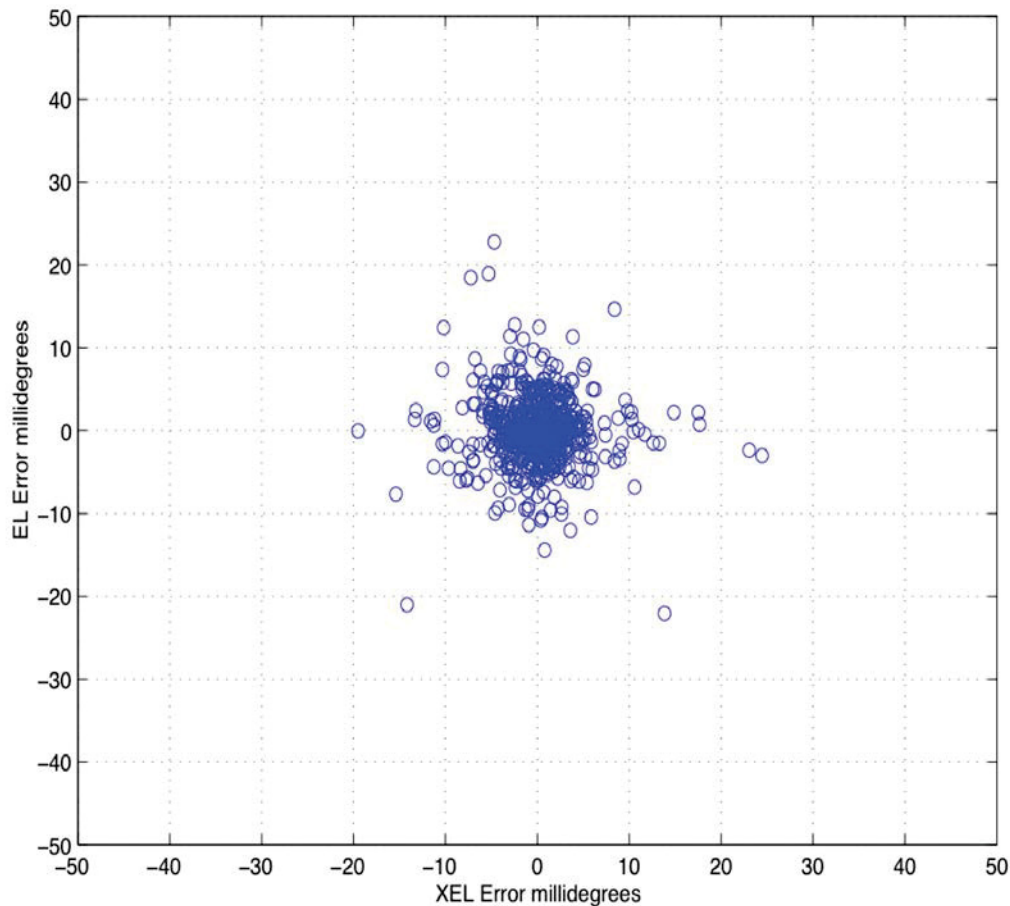
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## RF Performance - Antenna

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- Pointing: Measured at 32 GHz. Obtained consistent pointing performance, pointing error  $< 0.005$  degrees



**Figure 28.** Measured pointing accuracy of 12-meter breadboard antenna

## RF Performance – 12m Antenna Efficiency – Opening Volley

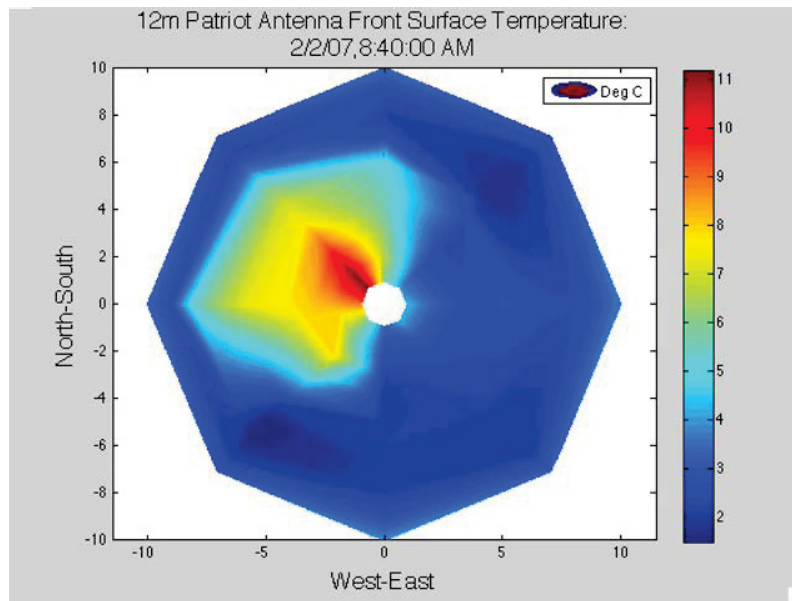
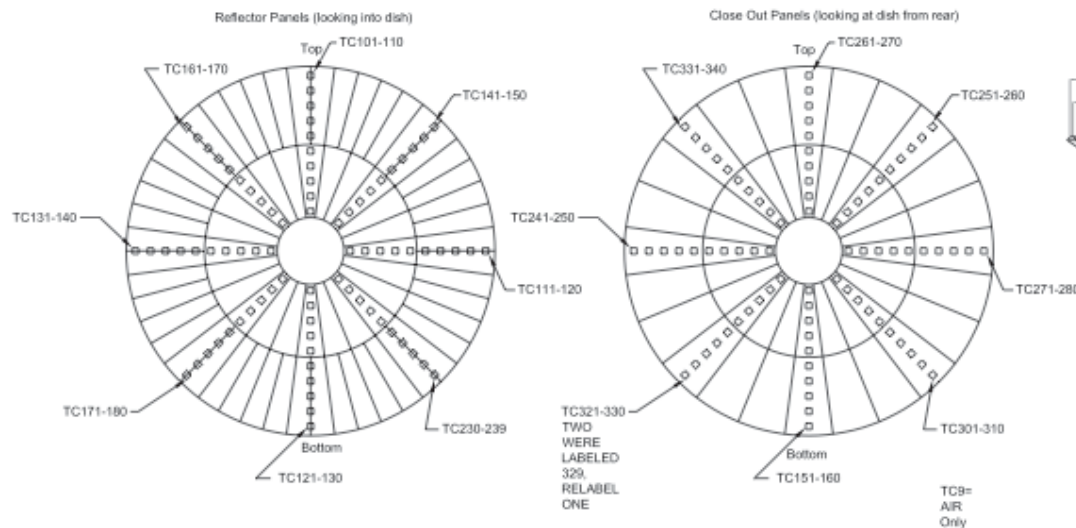
35

- Recall the foreshadowing from the photogrammetry measurements of the reflector from morning to noon. Many dB's of loss!
- Deformations seem to be associated with thermal load on the antenna
- The antenna was subsequently instrumented by 150+ thermal sensors.
  - Data logged every minute for many (many) weeks
  - Initially data was plotted in Excel spreadsheets along the line of sensors (see next chart)
  - Data was extremely difficult to understand so a Matlab visualization was developed
    - ✧ Results were enough to suggest that the thermal load was enough to be of concern
- Determined that the loss was mainly due to large scale deformations of the reflector that moves the focal point along the focal axis of the antenna
  - The mechanical group in Section 333 provided a retrofit to the subreflector. An automatically controlled motorized system was installed that could move the subreflector by approximately +/- 20 mm



# RF Performance - 12m Antenna Thermal Loading

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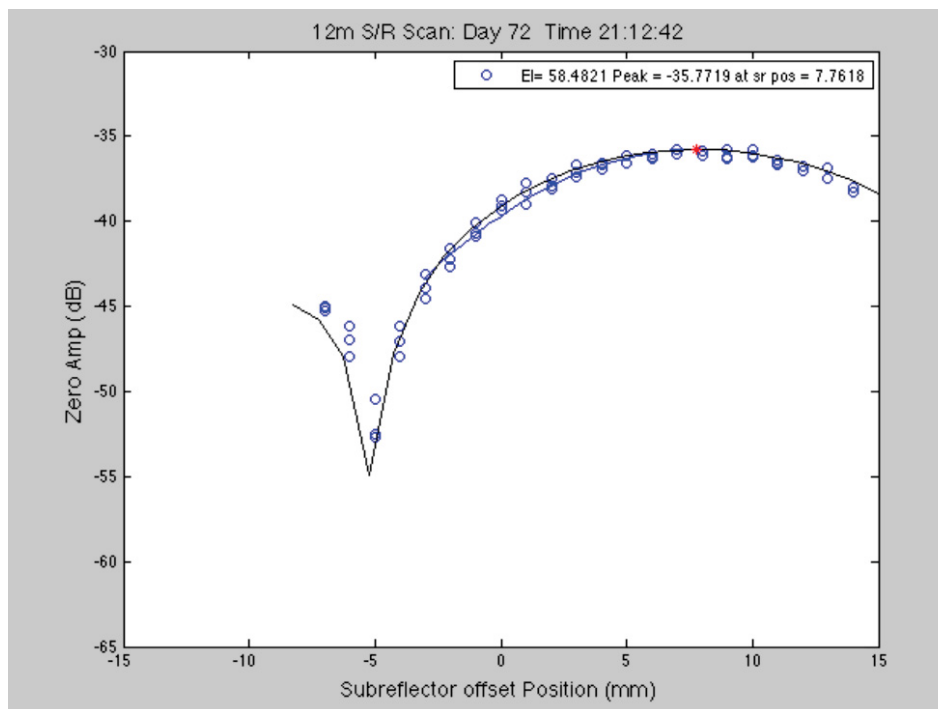




# RF Performance - 12m Antenna Focal Position Change due to Thermal Load

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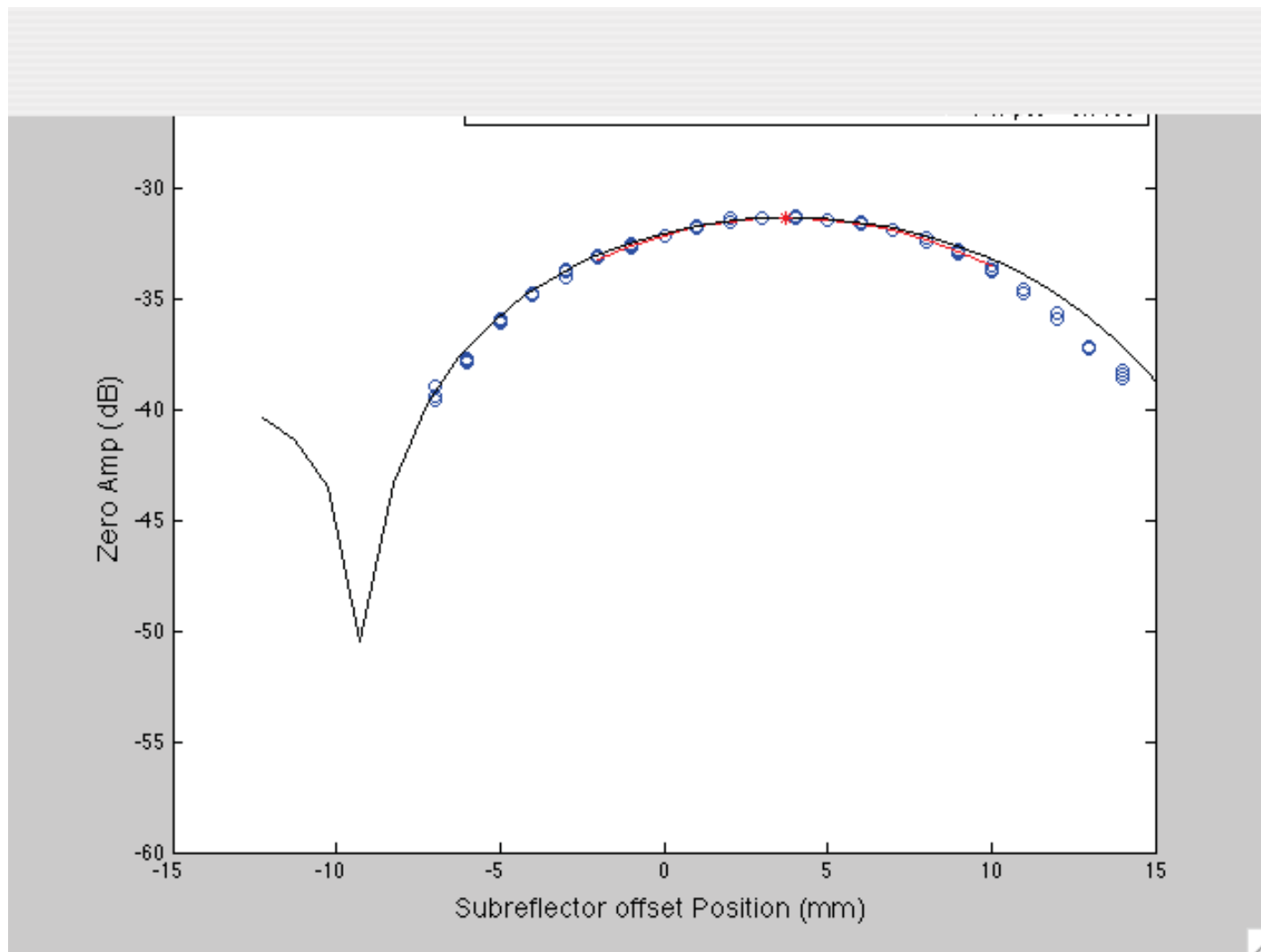
- Subreflector positioner added by the mechanical group in Section 333
  - Allowed movement about expected best focal position  $\pm 15$  mm
- Used interferometry to measure subreflector position that maximized the signal
  - Measured peak level (relative)
  - Measured peak position
  - Show plots of representative day/night subreflector curves
  - Show plot of what peak position does versus time of day and elevation





# RF Performance - 12m Antenna Focal Position Change due to Thermal Load

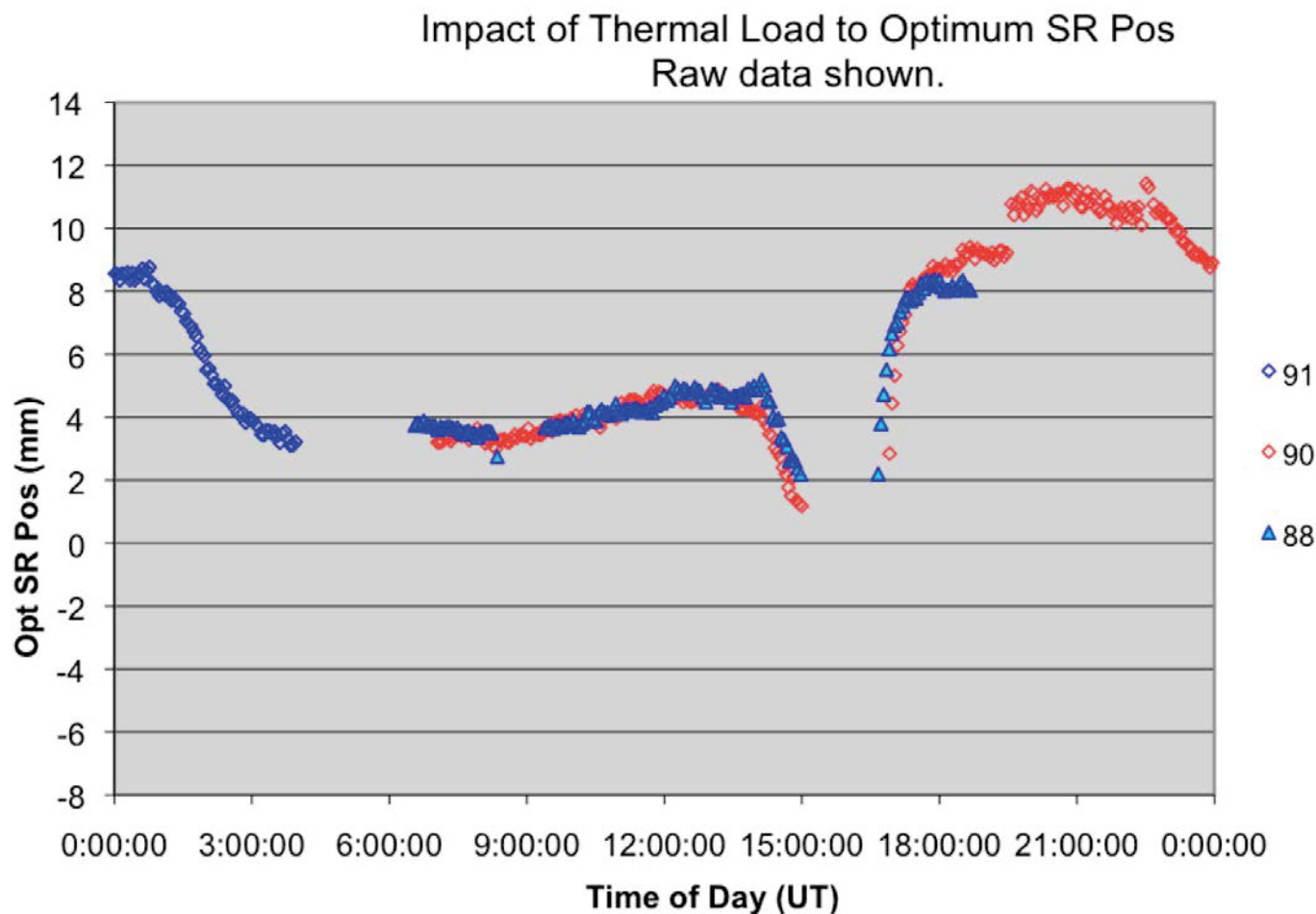
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# RF Performance - 12m Antenna Focal Position Change due to Thermal Load

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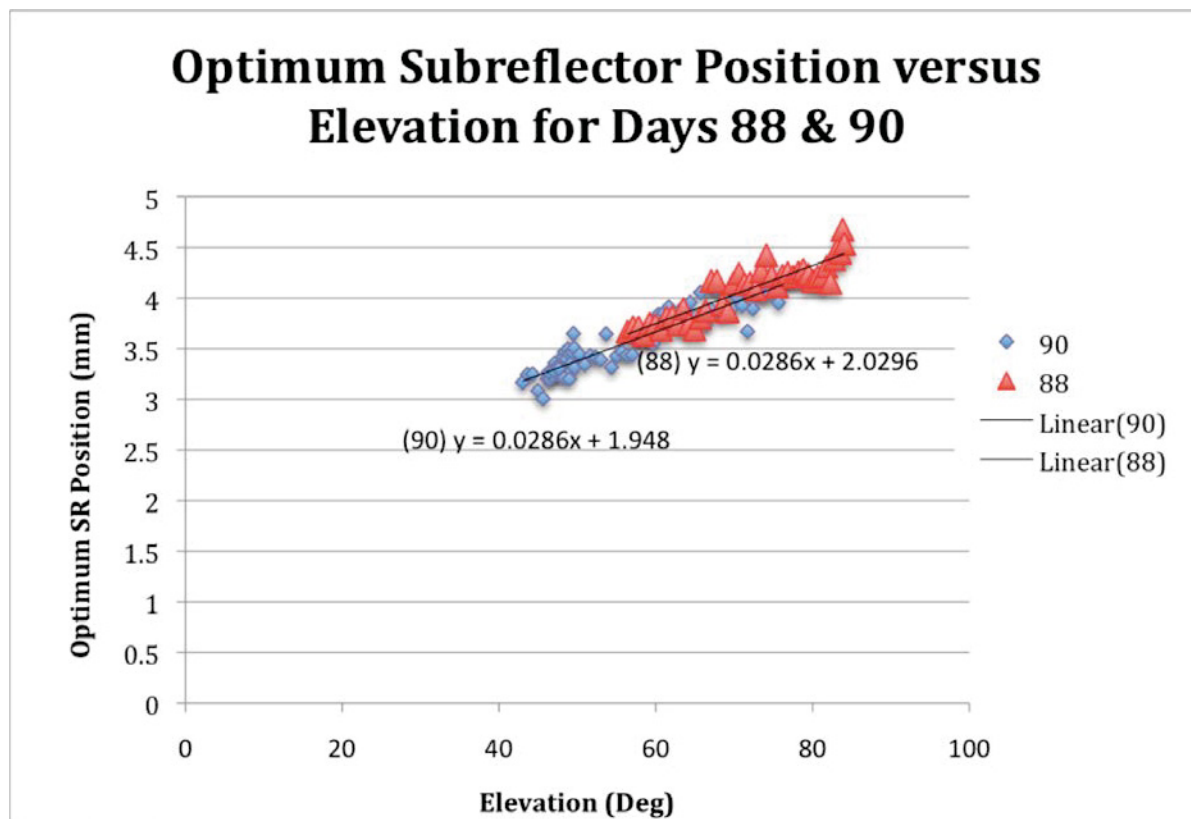
- Plot of the locus of points representing the optimum subreflector position as a function of time-of-day. Three days shown



# RF Performance - 12m Antenna Focal Position Change due to Thermal Load

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- Plot of the Optimum subreflector Position versus Elevation for Days 88 and 90. Linear fits to the data show elevation dependency during isothermal conditions (i.e., during the night time).
- EUREKA! The elevation dependency is clearly obvious.
  - The FEA done several years earlier at the contractor CDR showed a change in antenna focal length of 2.46 mm.
  - Extrapolation of the linear fit to this data shows change in antenna focal length of 2.57 mm.

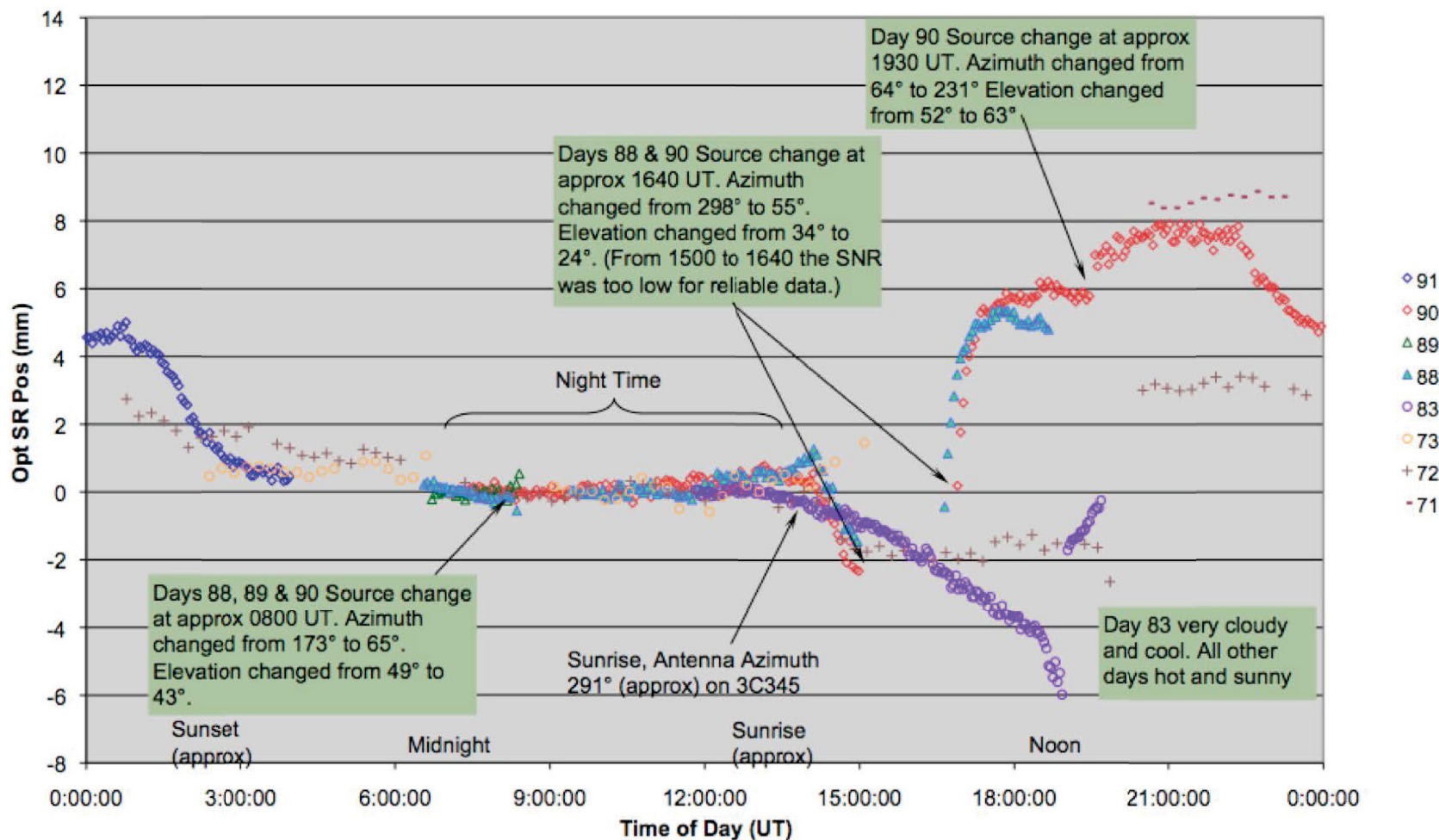




# RF Performance - 12m Antenna Focal Position Change due to Thermal Load

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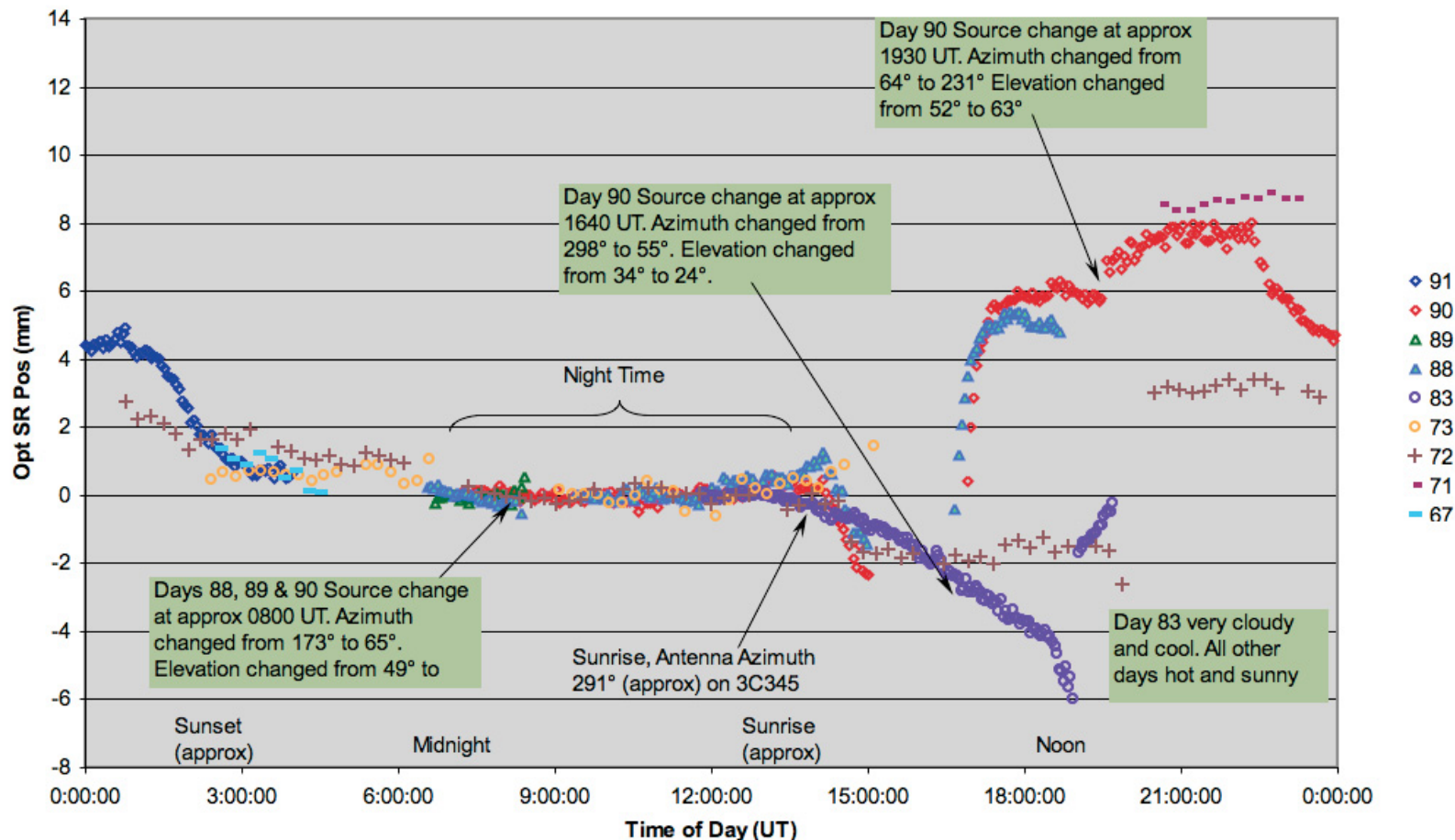
**Impact of Thermal Load to Optimum SR Pos**  
**Effects of elevation removed. Normalized to 0mm at night.**



# 12m Thermal Performance

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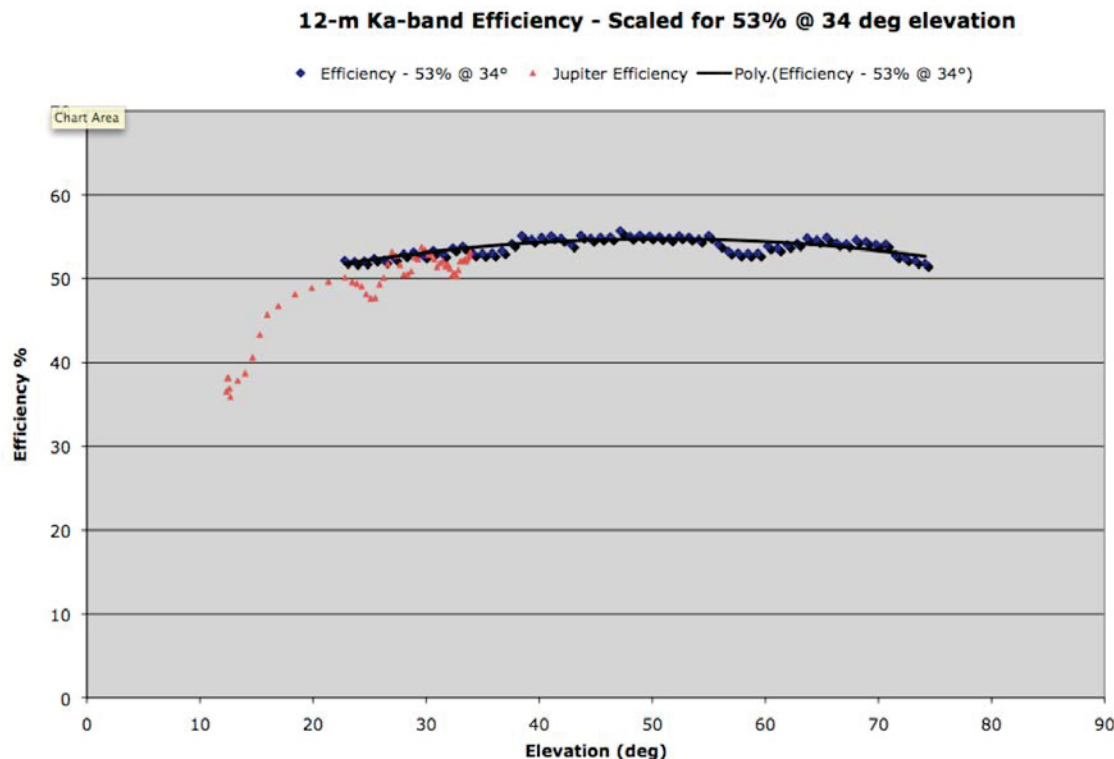
**Impact of Thermal Load to Optimum SR Pos**  
**Effects of elevation removed. Normalized to 0mm at night.**



## RF Performance – 12m Antenna Efficiency – Revisited

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- So, now that we understand that efficiency measurements should only be done in thermal quiescent conditions, i.e., in the dead of night, we press forward with antenna efficiency characterization.
  - Use Jupiter since it's the strongest calibrator at the time. Rises to max elevation of 35° EL
  - Perform same measurement on secondary calibrators 2C273 and 3C345, scaled to the efficiency of Jupiter at 34° EL.
  - Maximum Efficiency = 53% (Expected to be 60%...ugh...)



# RF Performance – 12m Antenna Efficiency – Revisited

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Factor	Predicted Efficiency Factor	Actual Efficiency Factor <sup>†</sup>	Comments (See Text for more detail)
Physical Optics Efficiency	0.865	0.796	Actual feed-horn patterns measured on antenna range rather than predicted patterns.
RMS Main Reflector	0.846	0.846	In thermal quiescent conditions the RMS is 0.012" as expected
RMS Subreflector	0.982	0.982	Measured RMS is 0.004" as expected
I <sup>2</sup> R (Main and Sub)	0.998	0.998	Small contribution. Measured subreflector using radiometer with and without metal tape covering. No effect.
Feed VSWR	0.999	0.999	Measured on network analyzer.
Feed Support Blockage	0.85/0.90	0.85/.090	Range of blockages typical for low profile feed supports.
Z-axis focus	1.0	0.955	± 2 mm variation due to different isothermal temperatures from one night to another.
Lateral positioning of feed	1.0	0.996	Using unbalance in sidelobes to estimate lateral displacement. Approximately 1.1 mm. Efficiency loss calculated for this displacement.
Total Efficiency	0.609/0.645	0.533/0.564	

... Phew!! Figured it out...





# Today's Agenda

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  - Cassini Combining Results
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# Spacecraft Signal Combining

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- Two spacecraft chosen to demonstrate performance of the system
  - Mars Reconnaissance Orbiter (MRO)
    - ✧ X-band (8-8.8 GHz)
    - ✧ 3 and 6 MSPS
    - ✧ Link budget developed:
      - 12m antenna can detect carrier; perform symbol synchronization
      - Telemetry decoding at 3 MSPS possible with combined antennas
      - Telemetry BW=6 MHz...covers 5 frequency channels in the filter bank and tests decomposition of the telemetry in frequency and re-synthesis in time
  - Cassini Orbiter (at Saturn)
    - ✧ Ka-band (31-38 GHz)
    - ✧ Carrier only
    - ✧ Able to characterize  $P_c/N_0$  for individual elements and the combined array
    - ✧ Drawbacks of carrier-only:
      - only one frequency channel of the analysis filter bank
      - Phasing in a single 1.25 MHz wide filter bank channel will be difficult

# MRO Combining Results: X-band

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- Signal characteristics:
  - 3 MSPS telemetry signal
  - Carrier 8439.6 MHz
- RFI present at JPL during observations
  - Mitigated by zeroing out the channels with this unwanted signal
- Cross correlation measured with the 12m antenna used as reference
- Predicted carrier to noise estimated and compared to measured results

**Table 1.** Average and standard deviation of phase for the cross-correlation of the breadboard array 12-m antenna with the two 6-m antennas of the breadboard array with phase feedback during combining.

Baseline	Phase Average	Phase Standard Deviation
ANT1-ANT3	1.1 degrees	0.78 degrees
ANT2-ANT3	1.1 degrees	0.61 degrees

**Table 2.** Link budget carrier to noise predictions and measurements for X-band MRO telemetry on DOY 268 at 14:35:00 UTC

	Ant1 (6 m)	Ant2 (6 m)	Ant3 (12 m)	DSS14 (70 m)
Est. Antenna Efficiency	0.69	0.69	0.74	0.70
Measured System Noise Temp (K)	20.4	22.4	22.7	19.8
Pc/No (dB) Predicted	48.9	48.5	54.8	70.45
Pc/No (dB) Measured	48.7	49.1	54.2	65.6

**Table 3:** Comparison of measured combined carrier to noise ratio to predicted for breadboard antennas observing the X-band MRO telemetry. Measurement uncertainty is about 0.1 dB.

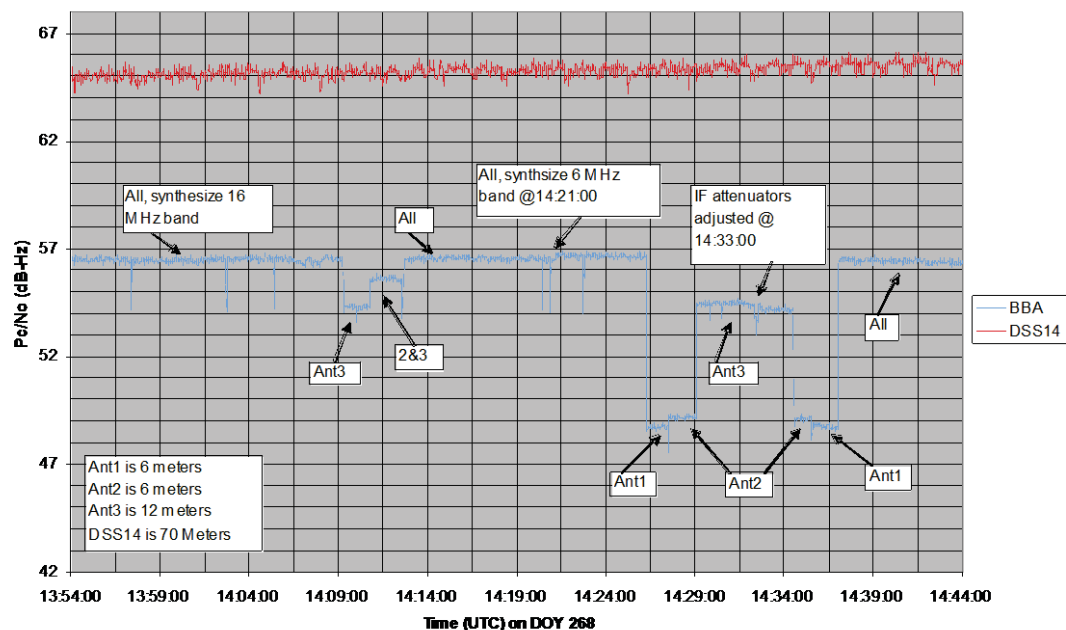
Ant 1	Ant 2	Ant 3	Combined (Measured)	Combined (Predicted)	Combining Loss
48.8 dB +/- 0.1 dB	49.2 dB +/- 0.1 dB	54.3 dB +/- 0.1 dB	56.4 dB +/- 0.1 dB	56.3 dB	0.1 dB

# Breadboard Array System

## Performance: X-band

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Measurement of the carrier to noise ratio of an MRO telemetry signal on 2007 DOY 268 for breadboard array antennas with and without combining. The measurement of  $P_c/N_o$  for the same telemetry signal as received by DSS14 (a 70 Meter antenna) is included for comparison. Data rate = 3 Mbps, Symbol rate = 6 MSps, Mod Index = 85° .



	Ant1 (6m)	Ant2 (6m)	Ant3 (12m)	DSS14 (70m)
<b>Estimated Antenna Efficiency</b>	0.69	0.69	0.74	0.70
<b>Measured System Noise Temp (K)</b>	20.4	22.4	22.7	19.8
<b>Pc/No (dB) Predicted</b>	48.9	48.5	54.8	70.45
<b>Pc/No (dB) Measured</b>	48.7	49.1	54.2	65.6



# Cassini Combining Results: Ka-band

- Signal characteristics:
  - Carrier-only
  - 32.0246 GHz
- No RFI...but weather was a concern
- Delay and Phase predicts based on RA/DEC
- For carrier-only signal only the single channel that the signal existed in was used to phase up the array
  - Delay feedback was disabled as delay offset measurements were not possible
  - Phase feedback was enabled based on measured phase offset of single channel
- Carrier to noise ratio measured and compared to predicted values

**Table 4:** Phase of the cross-correlation of the 12-meter reference antenna with the two six meter antennas for the Cassini carrier on DOY 267 while the phase feedback loop was enabled.

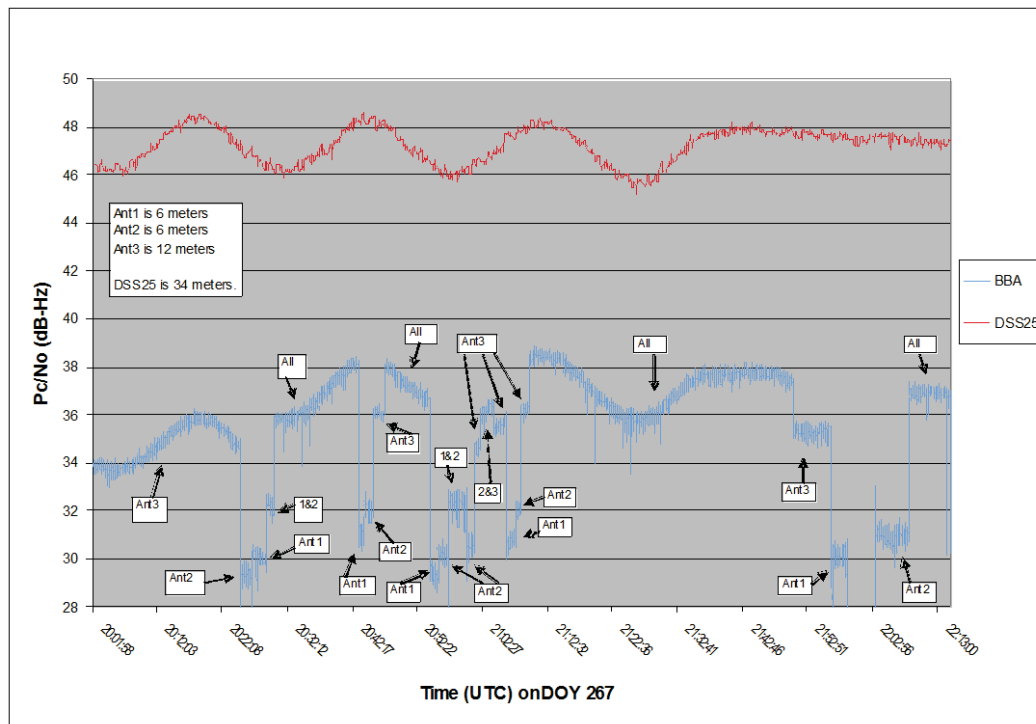
Baseline	Phase Average	Phase Standard Deviation
Antenna 1 to antenna 3	0.17 degrees	23.3 degrees
Antenna 2 to antenna 3	-0.18 degrees	26.0 degrees

**Table 5.** Measurement of Pc/No for Cassini carrier using breadboard antennas. Measured values are compared to predicted values.

"Ant1"	"Ant2"	"Ant3"	"All" Combined (Measured)	Combined (Predicted)	Combining Loss
30.2 dB +/- 0.25 dB	30.9 dB +/- 0.25 dB	35.4 dB +/- 0.25 dB	37.25 dB +/- 0.25 dB	37.54 dB	-0.29 dB

# Breadboard Array System Performance

Measurement of the carrier to noise ratio of a carrier signal at 32.024 GHz from the Cassini spacecraft on DOY 268 for breadboard array antennas with and without combining. The measurement of Pc/No for the same carrier signal as received by DSS25 (a 34 Meter antenna) is included for comparison.



	Ant1 (6m)	Ant2 (6m)	Ant3 (12m)	DSS25 (34m)
Distance (AU)	10.11	10.11	10.11	10.11
Frequency (GHz)	32.2222	32.2222	32.2222	32.2222
Estimate d Antenna Efficiency	0.60	0.60	0.40	0.68
Measured System Noise Temp (K)	51	50	45	45
Pc/No (dB) Predicted	30.6	30.7	35.4	46.7
Pc/No (dB) Measured	30.2	30.9	35.4	47.7



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## Arraying - Other Applications

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- This talk considered an array that is specifically suited to spacecraft communications, however there are other applications for this technology that can be pursued:
  - Signal processing provides very wide bandwidth **real-time interferometry** in addition to the combining of the antenna signals.
    - ✧ The system developed here includes a 500 MHz correlator. Wider bandwidths are also achievable
  - Arrayed downlink can provide an inexpensive large aperture for reception of
    - ✧ **bi-static radar** signals
    - ✧ **orbital debris identification**
    - ✧ **Other orbital object identification**
  - Arrayed uplink for deep space communications is being developed.
    - ✧ Unique since there is no feedback available to support phasing of the signal (due to the long round trip light time)
    - ✧ Can make use of  $N^2$  effect to achieve large EIRP (terawatt levels)





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# Summary

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- An architecture for an array of many small antennas for spacecraft communications has been supposed, developed, and breadboarded.
  - Requires different paradigm for operations
  - Requires different arraying signal processing than currently used
  - Lends itself to subarraying to support multiple targets simultaneously, or to provide the biggest band for the buck
  - Presented performance requirements for array elements
  - Presented performance requirements for array system
- Breadboard array described
  - Element performance shown
  - Array combining system developed to sum signals
  - System performance shown
- The ability of a large array of small antennas to greatly increase the downlink performance has been demonstrated for both X-band and Ka-band
  - MRO testing from Mars distance complete through a symbol stream processor at 6 MSps
  - Cassini testing on carrier from Saturn distance

## Current Plans

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- NASA/JPL have completed the study of an array of large antennas that included both the performance and cost aspects.
  - Performance is well documented and accepted
  - Cost must be further developed for this new architecture
    - ✧ Total life cycle costs are not fully characterized
    - ✧ Implementation costs are known well enough to proceed
    - ✧ Operations and maintenance costs are not known well enough at this time
  - An array of sufficient size ( $N=10$  to  $20$ ) to capture historical data for operations and maintenance costs must be constructed and operated for a period of time (approximately 5 years) in order to really understand those costs.
- Current mission load requires more aperture at all complexes by 2016/2017
  - Budget and time does not exist to construct a prototype array of small antennas to ensure that this architecture will meet NASA's availability requirements in time to deploy such arrays at all locations of the DSN.
- The currently funded budget will construct more aperture and utilize the arraying technologies developed here
  - Antennas will consist of current design 34m Beam Waveguide systems
  - Multiple antennas at each complex
  - Modern signal processing hardware based on these designs will be implemented